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EPIC

Report

D2.4 Studies and Analysis of Requirements vs. Application Domains

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1 INTRODUCTION

In the frame of the Electric Propulsion Innovation & Competitiveness (EPIC) project, (grant number 640199) and more concretely its Work Package 2 “Technology Mapping & Application Requirements”, this document has been produced with the aim to be the main output of Task 2.3 “Studies and Gap Analysis of requirements vs Application Domains”.

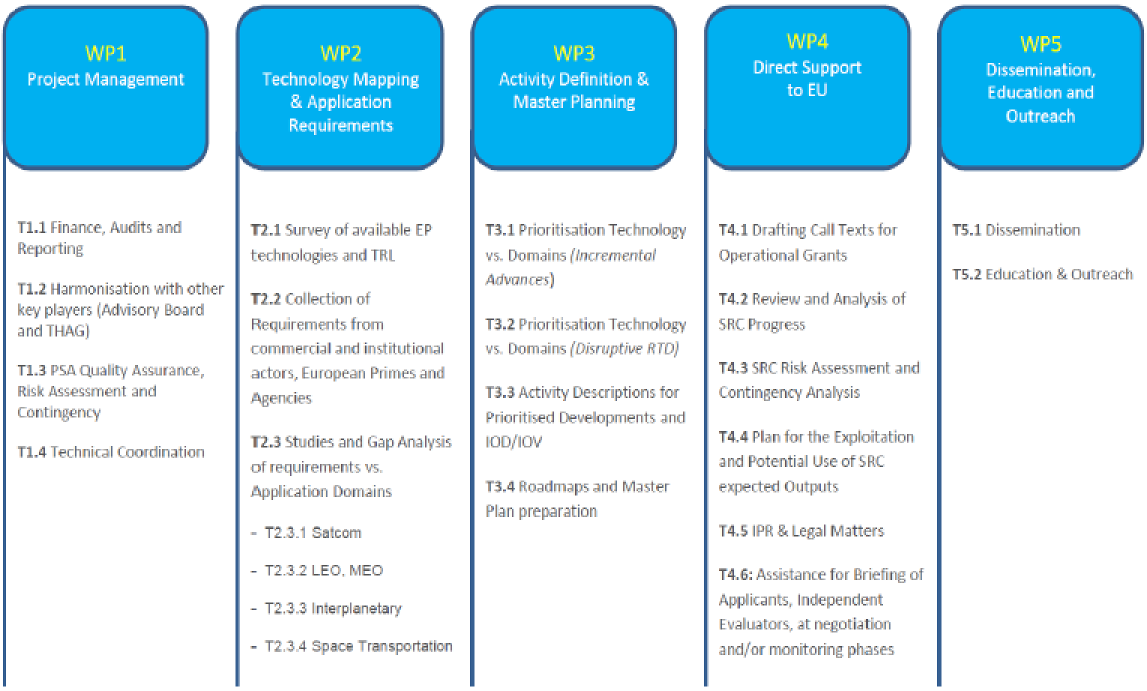

Figure 1-1: EPIC Work Logic

This document gives for the Electric Propulsion System (EPS) and its components an overview of the critical review and gap analysis to match the identified requirements (RD5) and the available/perspective EPS and EPS-related technologies (RD4) in order to create the basis for the selection and the creation of a roadmap of technologies and activities to be developed and pursued for the evolution of the EPS in the Strategic Research Cluster (SRC) devoted to Electric Propulsion for Space inside H2020.

The different types of EPS Thrusters addressed are:

- Ion Engines (GIE)
- FEEP thrusters
- Hall Effect Thrusters (HET)
- High Efficiency Multistage Plasma Thrusters (HEMPT)
- Pulsed Plasma Thrusters (PPT)
- Arcjets
- Resistojets
- Magneto Plasma Dynamic thrusters (MPDs)
- Colloid thrusters
- Quad Confinement Thrusters (QCT)
- Electrodeless plasma thrusters (including Helicon Plasma Thruster, HPT)

The different types of EPS components addressed are:

- Pointing Mechanism
- Pressure Regulators and Flow Management elements
- Power Processing Units
- Power Generation and Distribution
- Test Facilities and Diagnostics
- Development tools
- Cathodes/Neutralisers
- New concepts and technologies

The different types of missions and requirements addressed are:

- LEO (e.g. Earth Observation, Earth Science, constellations)
- MEO (e.g. Navigation)
- GEO (e.g. telecommunications)
- Space Transportation (e.g. launcher kick stages, space tugs)
- Space Science, Interplanetary, and Space exploration.

2 REFERENCE DOCUMENTS

[RD1] *European Space Technology Harmonisation Technical Dossier – Electric Propulsion Technologies*, Ref. ESA/IPC/THAG(2014)12, Issue 3, Revision 1, Draft.

[RD2] *European Space Technology Harmonisation Technical Dossier – Space Mechanisms – Electric Propulsion Pointing Mechanisms*, Ref. TEC-MSM-2009-4-In-JML, Issue 2, Revision 2, Technical Note.

[RD3] *European Space Technology Harmonisation Technical Dossier – Power Management and Distribution*, Ref. ESA/IPC/THAG(2013)7, Issue 3, Draft.

[RD4] *EPIC D2.1 EP technologies database, Issue 1.2,* EPIC-CNES-2.1-RP-D2.1-1.2

[RD5] *EPIC D2.2 EP requirements database, Issue 1.1,* EPIC-CNES-2.2-RP-D2.2-1.1

[RD6] ESA Activities in the field of Electric Propulsion, J. Gonzalez del Amo.

[RD7] *European Space Technology Harmonisation Technical Dossier – Chemical Propulsion -Components*, Ref. TEC-SGH/2011/97/CPCTD, Issue 3, Revision 2, Draft A.

[RD8] *EPIC D2.3 EP Workshop, Issue 1.1,* EPIC-CNES-2.3-RP-D2.3-1.1

3 LIST OF ACRONYMS AND ABBREVIATIONS

ALP: Ablative Laser Propulsion

EBB: Elegant BreadBoard

ECRA: Electron Cyclotron Resonance Acceleration thruster

ECSS: European Cooperation for Space Standardization

EO: Earth Observation

EOL: End of Life

EOR: Electric Orbit Raising

EP: Electric Propulsion

EPPM: Electric Propulsion Pointing Mechanism

EPS: Electric Propulsion System

FEEP: Field Emission Electric Propulsion

GEO: Geostationary Earth Orbit

GIE: Gridded Ion Engine

GSO: Geo Synchronous Orbit

HEMP-T: High Efficiency Multistage Plasma Thruster

HET: Hal Effect Thruster

HPT: Helicon Plasma Thruster

IBS: Ion Beam Shepard

IT: Total Impulse

MPD: Magnetoplasmadynamic thruster

NEP: Nuclear Electric Propulsion

NGGM: Next Generation Gravity Missions

NSSK: North-South Station Keeping

PCU: Power Conditioning Unit

PCDU: Power Conditioning and Distribution Unit

PIT: Pulsed Inductive Thruster

PPT: Pulsed Plasma Thruster

PPU: Power Processing Unit

PR: Pressure Regulator

PSCU: Power Supply and Control Unit

QCT: Quad Confinement Thruster

R&D: Research and Development

SEP: Solar Electric Propulsion

SRC: Strategic Research Cluster

TRL: Technology Readiness Level

VAT: Vacuum Arc Thruster

4 OBJECTIVES AND CHALLENGES

The main objective of these analyses is to identify the gaps in the capabilities of EPSs and their related technologies that should be filled in order to increase the competitiveness and usefulness of European EPSs in the 2020-2030 timeframe.

Finance is the driving criteria for commercial missions such as for communication satellites and some Earth observation missions. Performance is often the driving criteria for institutional missions such as science and exploration. Space transportation has to serve both commercial and institutional needs and therefore is often a compromise between both drivers.

In order to achieve this goal, the following steps are to be taken:

- with the inputs from RD5, perform a critical review of the mission requirements that are applicable to EPS and EP-related technologies, identifying both the functions that could be fulfilled by EP and the performance key parameters that should be taken into account;
- map the EP technologies, both in their current and expected performances, to the mission requirements previously defined, in terms of the key parameters selected. Also, additional considerations on the EPS characteristics should be taken into account;
- identify the set of the mission requirements that are not fulfilled by current EP technologies, and the likely candidates to fill the gap, if any.

The performance of these analyses has several challenges:

- Identifying mission requirements for very different types of missions is complex, and information is often incomplete, especially when commercial applications are being studied.
- The information on the EPS is not homogeneous, and in several key factors (cost, development time, integrability) there is no objective way to set a concrete value.

The results of these analyses will serve as inputs for the prioritization of technologies and the establishment of Roadmaps for the incremental technologies (HET, GIE and HEMPT based EPS) and for the disruptive technologies during the Work Package 3.

5 METHODOLOGY

In order to ensure coherence and comparability of the studies, a common basic methodology is defined, which does not prevent from adding additional elements when needed.

The analyses should include at least the following elements:

Definition of mission requirements to be used in the analysis

The analysis should identify:

- Which mission requirements have been assumed for each analysis (RD5).
- Identify the key mission parameters that will be used to perform the mapping, including a rationale of why they are selected.
- Identify other requirements that are also relevant for this mapping.

Perform the mapping between the mission requirements and each type of EPS technology

- For each technology, as defined in RD4, two comparisons should be defined, in terms of the key parameters, for the performances that can be obtained with the technology:
  - With current systems (high TRL 8-9).
  - With expected performances (currently with low TRL) in near future (by 2020-2030).
- By means of plots or tables the requirements and the key technology parameters are presented for each EPS technology.

Analyze the mapping

- Identify the gaps, as the set of mission requirements that are not met by current technologies (high TRL). Divide the gaps between two types:
  - Should be met by expected performances or incremental optimization and evolution of the current systems.
  - Would not be met by current systems, and thus require incremental advances or new disruptive developments.
- In addition, identify also gaps that, while they could be covered by the technologies in the point above if only technical parameters are taken into account, there are serious doubts about the feasibility (number of thrusters to be added to the mission, cost, complexity to integrate, etc.).
- Identify the technologies that are closest to being able to fill the gaps. This would be a qualitative assessment.
- Identify the technologies that are intrinsically unable to fill the gaps, due to characteristics of the concept.
- Summary of the results of the analysis, identifying the EPS candidate technologies and the gaps to be covered by these EPS (High TRL / Low TRL).

Criteria and Guidelines for the Analyses

These are the set of criteria to cover all possible aspects of the analysis (see Table 5-1). The availability of some of them is limited and therefore the analysis will need to be done making, where needed, particular assumptions.

Costs/Feasibility	recurring costs
	non recurring costs
	Starting TRL and relevant justification
	Development Planning and Risks Analysis
	Level of dependence on Non European key technogies
	Level of dependence on Non European testing facilities, diagnostic capability
	Level of dependence on flight qualified technologies
	Critical components (PPU, FCU, etc.)
Flexibility	Versatility w.r.t. Different classes of missions (for each EP engine identify the possible classes of missions)
	Versatility w.r.t. Different applications (for each class of missions identify the possible applications)
	Versatility w.r.t. propellants (compatibility whith different propellant)
	Throttability, controllability (i.e. fine thrust regulation, modularity)
	Commonalities w.r.t. other EP building blocks
	Scalability
Competitiveness	Expected competitive position in the european and non european market (specify if short/medium or long term scenario) taking into consideration future missions
	Valorization of competiencies/technologies already developed at european level in other national and international project
	Performances gain due to disruprtive technology advacement
	Potential Spin off for cross related fields
	Possible integration in launch systems worldwide
Impact on the host -system (including the launcher)	Expected saving on the host-system (weight, power etc.)
	Interface compatibility between the EP and the host system
	Expected host-System delta performance (Mission benefits)
European Non-Dependence	Contribution and impact of the technology in ensuring European Non-Dependence

Table 5-1: Criteria for future prioritization of technologies

Technically speaking the following main parameters are identified:

Mission Total Impulse: Total impulse, IT, is defined as the overall change in momentum caused by the propulsion system thrust acting over time. For a given thrust level, this figure measures the lifetime that is required for the thruster to be fired. Total impulse is directly related to the mission Delta-V. Once in obit, Delta-V can range from several m/s for orbit maintenance and attitude manoeuvres for small LEO missions to several km/s for interplanetary missions.

Thrust level: The thrust, T is generated by the momentum exchange between the thruster exhaust and the platform. Due to the nature of the expelled plasma species in electric propulsion thrusters, the thrust levels are in the order of mN. High efficiency high power EP thrusters can provide a few N of thrust.

Specific Impulse: Isp is the premier measurement of Space propulsion thrusters performances. This parameter compares the thrust derived from a system as a function of the propellant mass flow rate. In electric propulsion, it ranges from several hundreds of seconds for small escalations of Resistojets and ITs to six or seven thousand seconds for high performance Ion Thrusters.

Thruster input Power: The available power onboard the Platform, can range for some watts in small platforms, going through a few tenths of kilowatts for exploration platforms and GEO communication platforms and up to MW for prospective missions implementing nuclear reactors. Depending on the mission concept and associated platform architecture, this would imply a certain level of power available for each of the thrusters. From a functional and operational point of view, the main requirements to be derived should detail.

Manoeuvring needs: Propulsion systems can serve for orbit transfer and/or maintenance as well as for attitude control or reaction wheels offloading. All these possible applications such as precise positioning or fine attitude control pose different requirements on the thrusters to be used.

Thrust vector orientation need: For some missions, the possibility of thrust vector steering is required. This can be performed using dedicated Thrust Orientation Mechanisms (TOMs). For next generation of Telecom platforms (NEOSAT, Electra, etc.) booms and Rotary Actuators will be used to perform the thrust vector capability. Other strategies may increasing the number of thrusters and modifying their combined thrusting profiles or, as preliminarily envisaged for HPT, modifying the magnetic field generated by the magnetic nozzle.

Throttleability: Thrust and Isp control possibility, with the ability to work in different performance points. Apart from this preliminary list, other performance, functional and/or interface requirements will be introduced in the specifications.

These are the guidelines followed during the analysis:

- All assumptions should be identified and explained.
- Additional specific criteria could be set for an EP system, technology, and component or test facility, as necessary.
- Each specific criterion should cover fully the range of possibilities in the state of the art and future trends regarding systems and components in order to allow comparisons and optimization.
- Special characteristics should be labelled binary or where possible with a simplified scale.
- TRL level can be inferred from details in RD4.
- Some estimation of the cost of development and recurrent cost may be introduced in the evaluation or description of each EPS or component.

In order to fill the gaps in the requirements part of the analysis, a set of generic requirements has been defined. For each type of analysis (GEO Satcom, LEO, MEO, Science/Interplanetary and Space Transportation), and where information is incomplete or lacking, it is recommended to perform an analysis of the EPS against three different levels of power:

- Lower power missions (≤1.5 kW)
- Intermediate power missions (1.5 – 10 kW), and
- High power missions(≥ 10 kW).

The use of power as a discriminating parameter is because the power level is often correlated with many of the other performances and parameters: Mission/Satellite type, number of thrusters to be installed, subsystem complexity, integrability, costs, technology maturity (TRL), etc.

6 BACKGROUND

The analysis will be centred on a set of mission types or applications in which it has been identified that EPS can be useful and that were reported in RD5. These examples of missions were organized based mostly on the type of orbit (GEO, MEO, LEO, Interplanetary) but also on the type of mission (science, interplanetary or space transportation).
These types of missions impose different requirements on the propulsion system, and at the same time offer different market opportunities.

Present European platforms as well as short term needs (3-5 years) were already presented in RD5, but will be summarised here as background information with the addition of the worldwide markets (when applicable) for the analysis to be performed.

6.1 Missions needs

For the studied missions, the technology is faced with operational needs and market perspectives which can cover:

- Electric transfer from GTO to GEO
- Station keeping
- Interorbital transfer
- Interplanetary cruise
- Continuous LEO operations (air-drag control)
- (extreme) fine and/or highly agile attitude control
- Long-endurance missions.

To cover a maximum of missions and use-cases, the EP subsystem has to be:

- Commercially attractive
- Of a modular design (with many recurring elements)
- Highly scalable, and
- Producible in higher quantities (industrialisation).

Table 6-1 presents the technologies that could be used in different application domains. Only technologies with TRL above 3 and whose predicted performances are known are included.

Operation	Telecom	Earth Observations	Scientific Satellites	Explorations	Navigation
Orbit raising	Ion Engines, HETs, Arcjets, HEMPTs, HPTs	Ion Engines, HETs, Arcjets, HEMPTs	Ion Engines, HETs, Arcjets, HEMPTs	Ion Engines, HETs, HEMPTs, MPDs	Ion engines, HETs, Arcjets, HEMPTs, QCTs
Interplanetary Primary Propulsion	N/A	N/A	Ion Engines, HETs, MPDs, HEMPTs, HPTs	Ion Engines HETs, MPDs, Arcjets, HEMPTs	N/A
Station Keeping	Ion Engines HETs, HEMPTs	FEEPs, HETs, Ion Engines, Arcjets, Resistojets, HEMPTs, PPTs,	FEEPs, Ion Engines, HEMPTs, HETs, PPTs	N/A	HETs, Ion Engines, Arcjets, HEMPTs, QCTs

		HPTs			
Fine Altitude Control	N/A	FEEPs, Ion Engines, colloids	FEEPs, Ion Engines, colloids	N/A	N/A
De-orbiting	Ion Engines HETs, HEMPTs, PPTs	Ion Engines HETs, HEMPTs, PPTs	Ion Engines, HETs, HEMPTs PPTs	N/A	HETs, Ion Engines, Arcjets, HEMPTs, QCTs

Table 6-1:EP technologies (already at TRL >3) that could be used in different application domains

6.2 Market Analysis

The trade-off for missions beyond Earth orbit considers very seriously the utilisation of electric propulsion.
The evolution of the launcher market together with the use of electric propulsion systems may reduce the requirement for the time elapsed since one satellite is launched and it is operational in the proper orbit if the cost of the launch is reduced. This opens the door to new trade-offs on the distribution of launch and satellite propulsion in order to reach orbit and also it allows for lower satellite thrust solutions to reach the proper orbit. This evolution in the need of propulsion for satellites can lead to a satellite system configuration breakthrough favouring the use of electric propulsion.

6.2.1 Present and short term markets

Telecommunication

The largest market for electric propulsion is in commercial telecommunications satellites.
Today, this market is dominated in the West by a small number of American and European suppliers, namely Boeing, Space Systems Loral (SSL), Airbus DS, TAS and OHB.
They are all offering large telecommunication platforms (6.5 tons class). A largely independent market exists in the United States. Over the past decade commercial (and institutional) missions have taken the lead in exploiting the potential offered by electric propulsion. Both SSL and Boeing represent a significant threat to European commercial platform products and have each developed and flying platforms using electric propulsion.

SSL, Airbus DS and TAS currently offer a conventional approach with launch into GTO and a chemical propulsion transfer from GTO to GEO transfer and either chemical propulsion or electric propulsion systems for station keeping. Boeing offers an alternative approach with launch into Sun Synchronous Transfer Orbit (SSTO) with a combination of electric propulsion and chemical propulsion transfer to GEO, utilising the more efficient inclination change manoeuvres possible at the high apogee of the SSTO. All station keeping is then performed with electric propulsion.

Boeing is the market leader, having already developed two generations of platform using electric propulsion. Their 601HP platform was the first western commercial telecommunications bus to fly electric propulsion in the form of the XIPS-13 gridded ion engine. Their current generation bus 702HP uses its high-power capacity (up to 18 kW) to take full advantage of electric propulsion technology. The satellite is equipped with four 4.5 kW XIPS-25 gridded ion thrusters that feature high power orbit raising and low power station keeping modes. Once on station, the ion thrusters are used to perform all station keeping and spacecraft momentum control functions, repositioning and disposal.
SSL, through an agreement with Fakel (RU), have incorporated the SPT-100 Hall Effect Thruster into their LS-1300 platform. The four SPT-100 thrusters provide impulse for on-orbit inclination and eccentricity control as well as momentum control functions.
AEHF (Lockheed Martin) has also developed a series of A2100 satellites making use of the XR5 HET from Aerojet Rocketdyne.

The market has evolved in recent years, and it is continuing to evolve, based on a range of developments in launch services, platform technologies and operator requirements (RD5).

Launch services for the large commercial platforms are dominated in Europe by Proton and Ariane-5. These launchers have high prices for heavy payloads despite aggressive pricing strategy by Proton since 2013. Smaller platforms (< 3.5 tons) may be launched as dual payloads on Proton and Ariane-5 or as single payloads on Falcon-9. The possibility to launch dual payloads on Falcon-9 has emerged with Boeing's announcement of its small 702SP platforms (2 tons class). The development of re-ignitable upper-stages has introduced flexibility into the launcher market and allows a range of sub- and super-synchronous transfer orbits to be offered, reducing the overall velocity increment requirement on the spacecraft bus, and enabling electric propulsion to be considered for orbit topping / raising as well as station keeping.

Recent developments in platform technologies have been aimed at increasing the available payload fraction and accommodating larger and more powerful payloads. These developments have focused on the power subsystems and thermal control systems necessary to accommodate higher payload power. This has the advantage that more power can be made available for electric propulsion, especially during orbit transfer phase when the payload is not operational.

With respect to operator requirements, there is a sustained request for lower cost-per-transponder, coupled with a demand for larger transponder capacity and longer operational lifetimes. Despite the need of a higher capital investment many existing operators continue to be attracted by larger, higher-power spacecraft. However, in emerging markets where capital investment may be limited, smaller spacecraft may be more appealing. The telecommunications market is expected to continue to be dominated by the large spacecraft class, but with increasing interest in smaller platforms for expansion into emerging markets.

The described developments and trends in spacecraft and launchers are driving the total impulse requirement of electric propulsion to increasingly large values. Existing systems, with their limited total impulse capability, will not be capable to meet the future needs, so that development of higher power variants is becoming increasingly urgent.

Boeing's announcement in 2012 of sales of four of its new all-electric small platform (702SP) has produced significant interest in the commercial telecommunications market. Their aggressive approach to reduce satellite mass and allow dual satellite launches on the Falcon-9 launcher could lead to very significant reduction in operator costs. Although many of the satellite suppliers appear to be sceptical about the Boeing approach, they are all now reviewing their offerings with a view to increase competitiveness by increasing their use of electric propulsion.

It is clear that the trend to increased use of electric propulsion will continue in the telecommunications market and that higher power thrusters will be needed to meet both the orbit raising and station keeping needs of future small and large platforms.
Orbit raising applications would concern GEO satellites operated by the major telecommunication operators (SES, Inmarsat, Intelsat, Eutelsat) that can afford longer times to reach orbit with their satellites. The situation is considered not to be the same for smaller operators for which the time to orbit will continue being critical in the years to come, except when a newcomer operator tries to enter in the market (SATMEX - newly acquired by Eutelsat, Asian Broadcast satellites).

The number of GEO satellites launched per year in average from 2016 to 2021 by these large operators is foreseen to be 25, if all the operators are taken into account (source of data, Forecast International). One can make the hypothesis that half of the large operators GEO satellites will be equipped with electric orbital raising thrusters. The estimated market is then 12 satellites per year. The propulsion equipment for these satellites will be procured in open competition worldwide.

The European reaction to the changing launcher market and commercial platform developments in the United States is now underway.
Recently, Airbus DS was requested to provide 2 full EP GEO satellites for the operators SES-12 and Eutelsat 172B which is planned to be launched in 2017 with Ariane 5 and to arrive on its final orbit after 4 months of orbit transfer based on a HET EPS.

In addition, the European firms will benefit from the experience of the future platforms such as Spacebus Evolution, Alphabus extension, Neosat and Electra.

NeoSat which addresses the core (3-6 tons) of the telecom satellite market will be optimized for EP, both for raising the satellite into its final orbit after separation from its launcher, and for maintaining its operating position. The Neosat product lines will offer the option of all-electric, hybrid electric/chemical and all-chemical propulsion versions.
Electra is intended to cover the small to medium class platform applications. Electra is developed by OHB Systems in private-public-partnership with SES-Astra and ESA and will complete the SGEO platform offer which in the near future will be able to provide, full chemical, hybrid and full electric telecom platform architecture. The goal is to produce a small all-electric platform in the 2-2.5 tons class which can compete with the Boeing 702SP by offering low cost launch options. The baseline design considers a four thruster configuration (2 + 2) with each pair of thrusters mounted on a boom mechanism to allow repositioning between orbit raising and station keeping functions. The boom is necessary for wider plume divergence thrusters to avoid impingement on the spacecraft surfaces and arrays without significant reduction to the fraction of the thrust in the required direction of motion. The requirement for orbit transfer duration to be less than 200 days necessitates the use of 4.5 kW class thrusters for orbit raising. At this stage of the project both HET and GIE options are being considered.

The Boeing 702SP is a 2 ton/ 7.5 kW class platform which will use a common electric propulsion system, possibly based on the XIPS-25 gridded ion engine, for full orbit raising and all station keeping and momentum management functions.

SSL, are known to be engaged in qualifying the Fakel (Russia, RU) 5 kW SPT-140 HET. Once mated to a wide range deployment and positioning mechanism, developed by Loral, this will potentially offer a complete orbit raising and on orbit control capability using electric propulsion.

In parallel both Airbus DS and TAS are working on extended versions of their existing developments, these being based on the availability of 5 kW Hall Effect Thrusters and fully deployable thruster gimbals.

It is also expected that, due to the rapidly evolving market, the focus on mass reduction will start as soon as customers will start factoring in longer transfer times in their plans; this will imply the possibility to use high power GIEs or HEMP-Ts for telecoms applications.

In addition to the orbit-raising scenarios also hybrid satellites with electric propulsion for station keeping will most likely keep a non-negligible market share. In this application the thrust level is of less importance but the Isp determines the amount of required fuel. Therefore it is important to be prepared for a demand of high-Isp thrusters such as GIE and HEMP-T.

6.2.2 Medium to Long-Term developments

Telecommunication

In the US it is expected that Boeing will continue to market its large 702HP platform, using the XIPS-25 gridded ion engine system for the orbit topping and station keeping functions, toward operators seeking to replace or expand their existing fleets. In addition, it is expected that Boeing will target this platform at emerging markets, where the potential of low cost dual launch on Falcon 9 could significantly reduce capital investment cost for new markets.

Faced with such competition it is reasonable to expect that the “market” will over time demand that European platform providers match the worldwide competition, by offering orbit topping on its large platforms and developing small platforms with ‘all-electric’ orbit raising and station keeping functions.
All of the existing European platforms use the Fakel (RU) SPT-100 HET or the Snecma PPS®1350-G HET. Since the total impulse capacity of the both of these thrusters is limited, existing configurations cannot offer significant orbit topping in addition to the baseline station keeping functions. For the AlphaBus extended range, the situation is even more difficult. This platform range is targeted at for a maximum launch mass of 8.8 tons (maximum Ariane-5 ECA capability to GEO) and power extension to 22 kW. In this situation the total impulse capability of existing 1.5 kW thrusters (PPS1350) is marginal to perform the station keeping role, thus requiring the availability of thrusters with a higher total impulse capability.

High-power electric propulsion is therefore needed to cover this range of large Telecom applications within the AlphaBus frame. High-power electric propulsion is also needed to compete in the worldwide Telecom market and provide a substantial orbit-topping capability for the whole platform range. The AlphaBus extended-range platform will be designed to provide up to 90-days orbit-topping (with a maximum 200 m/s velocity increment), requesting an additional 1 MNs for the thruster total impulse capability.

In the long term high power thrusters will be needed to extend the total impulse capability of the electric propulsion systems and to increase the thrust available for orbit raising, so that larger fractions of the orbit raising function can be performed using electric propulsion while maintain an acceptable orbit transfer duration. High-power electric propulsion is also needed to save a larger fraction of the chemical propellant within the specified transfer duration and to extend the total impulse capability to be able to perform both orbit-topping and station-keeping with the same thrusters. With the increased thrust capability of the high-power thruster, wet mass savings are much more significant and the limitation of the maximum platform dry-mass is removed. In addition, novel thruster orientation mechanisms enable the operation of two thrusters in parallel with small thrust vector losses, rendering orbit transfer even more attractive.

Navigation / MEO missions

Future European MEO spacecraft will be mainly dedicated to the next generation of the European Galileo Navigation Satellite constellations. This will consist in a fleet of about 30 satellites using EP. This is a clear opportunity for the medium term perspectives of European EPS to be used in MEO/Navigation missions. The interest is not limited to the replacement of classic propulsion subsystems for station keeping manoeuvres but also on the possibility to reduce mass (or increase the payload mass) and optimize the launch strategy by reducing the number of launchers to be procured.
An EP system including 2 thrusters would be used on each satellite to perform EOR and SK manoeuvres. This implies about 60 EPS without counting any hardware to be built for test (Engineering model, qualification models, etc.) before the delivery of flight hardware. The developments and efforts made for the Telecommunication market will directly benefit this type of missions.

LEO missions

LEO missions cover different applications: they can be dedicated to Earth Observation (following the success of GOCE) and require very fine attitude control and drag compensation, Cubesats or nanosatellites.
Also with the very recent announcement by Space X of the establishment of a constellation of satellite for internet which will use EP on-board, the European providers should take the opportunity to compete worldwide for the provision of low power and cheap HET-based EP systems that will be required for station keeping manoeuvres.
For LEO, also some analyses show that, for instance, the potential market for on orbit debris removal could be just waiting for a spark to widely develop. ESA e.Deorbiting Mission phase A/B1 phase is an example of the on-Active Debris Removal Missions on-going studies focused on deorbiting a big Earth Observation satellite in which different propulsion systems are evaluated.

Therefore new ways of thinking and new development approaches, especially with very small satellites, shall be encouraged to develop competitive EPS system for those type of missions.

Science missions

In the case of science missions, the scientific requirements drive the propulsion system to be installed on board of the spacecraft and in certain cases EP is the enabling technology. It provides a better resolution, accuracy and savings of propellants. Several missions concepts using EP for science purposes are being proposed at ESA and are waiting to be selected for implementation. It can be for Earth Observation purposes (see above), or for Exploration missions (RD5).

Interplanetary and exploration

Despite the worldwide heritage of the use of EP for exploration missions (Smart-1, Deep Space 1, Hayabusa or Dawn), there are no European exploration and interplanetary missions approved and pending on propulsion decision candidate to be users of electric propulsion.

However it is clear from ongoing studies that once new planetary applications will be decided, at the beginning they will require very-high power and high Isp thruster and likely the development of disruptive technologies. It should also be noted that the availability of higher-power, higher-thrust EPSs is itself a mission enabler, as the propulsion capabilities are often the major constraint in the design of these types of missions. Any future availability of adequate EP systems in terms of power or lifetime will allow to perform extremely challenging missions.

Space Transportation

New missions are now reachable with increasing maturity of electric propulsion devices. Among this new set of possible missions, it is possible to simply mention tugging applications that can be classified between institutional (station servicing, cargo transfer beyond LEO, exploration missions, etc.) and commercial ones mainly focused on new strategy of payloads injection (use of a very low cost launcher and a re-usable tug up to the operational orbit) and on orbit servicing (maintenance, refuelling, ...). It is clear that the space tugs economics needs a proper analysis: indeed, ther is a significant cost to transport all the necessary propellant for multiple journeys and therefore an important trade-off between thrust, time, Isp and cost.

7 ANALYSIS

The analyses have been performed by looking at the different types of applications previously described, and within them, at different types of missions. Also a critical review of the results is performed to identify relationships and synergies between the results obtained for the different applications.

A first classification of missions could be defined based on the amount of power at disposal for the EPS. The missions can be categorized against three different levels of power:

- Lower power missions (≤1.5 kW)
- Intermediate power missions (1.5 – 10 kW), and
- High power missions(≥ 10 kW).

1.- LOW Power Mission:

For low power missions one may consider the following design drivers:

- Platform available power is less than 1,5 kW.
- Number of thrusters that can be on the platform is from 1 to 3.
- Upper limit power consumption for the EPS (0,5 kW to 1 kW).

Examples of such low power missions are small spacecraft with high Delta-V requirement, Cubesats, picosats with orbit maintenance requirements, Earth Observation (EO) missions with high power SAR instruments, formation flying missions in low altitudes, orbit raising, inclination change and End Of Life (EOL) deorbiting, precise formation flying constellations in L2.

The EPS function is mainly for drag compensation or orbit reconfiguration, de-orbiting, low power escalation for attitude control, etc.

These are the requirements taken from literature and preliminary mission analysis (RD5):

- Total impulse: > 2MNs.
- Lifetime: > 20,000 h.
- Thrust range : 1 – 50 mN
- Lower thrust (1 mN) for fly formation and fine attitude control
- Higher thrust (50 mN) for EOL de orbiting and orbit change.
- Thrust vectoring may be beneficial.
- Isp: between 500 s and 3,000 s.
- Power range: 500 -1500 W.

2.- INTERMEDIATE Power Mission:

For medium power missions one may consider the following design drivers for the EP system:

- Platform available power is between 1,5 kW and 10 kW.
- Number of thrusters that can be accommodated on the platform is from 1 to 8.
- Upper limit power consumption for the EPS is around 10 kW.

Examples of such missions are Satcom (GEO) spacecraft, Science interplanetary missions close to Moon and inner planets, robotic exploration, LEO active space debris removal mission using Ion Beam Shepard (IBS) concept, GEO orbit Station Keeping, Orbit transfer to GEO and orbit topping, the All-Electric Spacecraft in GEO, Solar Electric Propulsion exploration/science to the Moon, Inner planets exploration/science mission.

The EPS function is mainly dedicated to orbit raising to GEO, in GEO SK and the main propulsion for interplanetary missions.

These are the requirements taken from literature and preliminary mission analysis (RD5):

- Throttleability, requires to switch from optimum thrust to optimum Isp modes with the same thruster.
- Thruster depending on mission stage.
- Total impulse: 10 MNs.
- Lifetime: 15,000 h.
- Thrust range: 30 – 175 mN.
- Thrust vectoring may help to reduce the weight of steering system.
- Variable Isp in the range 1,000-4,500s.
- Power: current PPU technology is for 2.5 kW to 5 kW. In principle, the PPU design can achieve 10 kW but is not optimized for such a power range.

3.- HIGH Power Mission:

For High power mission, one may consider the following design drivers for the EP system:

- Platform available power is greater than 10 kW.

Examples of such missions would be very high power communication satellites, interorbital tugs for on orbit servicing and cargo transfer from LEO, Human exploration of solar system, Science missions to outer planets (Mars Sample return), SEP for Earth-Moon cargo transfer mission, mission to outer Solar System using NEP.

EPS function type: Main Propulsion during very long time periods with significant total impulse to be delivered

These are the requirements taken from literature and preliminary mission analysis:

- Throttleability, to perform on different thrust modes.
- Total impulse, 100 MNs.
- Lifetime, 18,500h.
- Thrust range: 0.4 – 2 N..
- Thrust vectoring may help to reduce the weight of steering system.
- Variable Isp as high as possible in the range 3,000-15,000s.
- Power: today PPU design can achieve 10 kW by grouping of blocks / clustering, For 20 kW one may need a further step in development and technology.

Missions covered by this classification and results of preliminary mission analysis from literature:

Power type	Mission Scenario	Functional requirement for EPS	Total Impulse (Ns)	Isp (s)	Power consumption (W)	Thrust (mN)	Live time (h)	N° thrusters	Special features

LOW	LEO/Small satellites with high Delta-V requirements	Drag compensation Orbit maintenance Orbit transfer Attitude control Orbit disposal	-	>500	<100	1-20	>4000	1-4	NR
LOW	LEO/Cubesats, pico-sats with orbit maintenance requirements	Drag compensation Orbit maintenance	>50	>500	<3-15	< 2	-	1	NR
LOW	LEO/Earth Observation Satellites with SAR High Power instruments	Drag compensation Orbit maintenance	> 1.5 10^6	500-4000	300 - 1000	1-20	>20000	2-8	NR
LOW	LEO/ orbit raising, inclination change and EoL deorbiting	Orbit maintenance Orbit disposal	>2 10^6	1000-4000	500-1500	30-175	>10000	1-2	NR
MED	Telecom/ GEO Station Keeping	Orbit maintenance Orbit disposal	1-2 10^6	1500-4500	1500-9000	30-175	3000-6000	2-8	Thrust vector orientation, Throttle ability
MED	Telecom/ GEO Orbit transfer and orbit topping	Orbit maintenance Orbit transfer Attitude control Orbit disposal	5-9 10^6	1200-5000	<9000 in transfer, <2000 in GEO	175-200	7000-12500	2-8	Thrust vector orientation, Throttle ability
MED	Telecom/GEO All Electric Spacecraft	Orbit maintenance Orbit transfer Attitude control Orbit disposal	3,5-15 10^6	1200-3000	<9000 in transfer and <2000 in GEO	90-200 for orbit transfer, topping and NSSK	>6500 for RCS 10000-20000 for orbit transfer and NSSK	2-8	Thrust vector orientation, Throttle ability
MED	Interplanetary/ SEP exploration/science to the moon	Orbit transfer	>1,5 10^6	>1500	1500-3000	30-200	>6000	1-2	Throttle ability

MED	Interplanetary/ Planets exploration/science	Orbit transfer	>10 10^6	2000-4500	≤9000	>200	>15000 (mercury)	2-4	Throttle ability
HIGH	Tugging applications in the Earth vicinity	Orbit transfer	> 3 10^7	>1500	>10,000	>200 each thruster	>4000	Several	
HIGH	Interplanetary/ Mars sample return mission using SEP	Orbit maintenance Orbit transfer Attitude control Orbit disposal	>8 10^7	2000-15,000	≥50,000	>4000	>17500	2	Throttle ability
HIGH	Interplanetary/ Outer Solar System using NEP	Orbit maintenance Orbit transfer Attitude control	>8 10^8	2000-15,000	≥50,000	>4000	>14000	8	Throttle ability
HIGH	Interplanetary/ Human exploration of Mars	Orbit maintenance Orbit transfer Attitude control	>3 10^9	2000-15,000	>10 10^6	> 4000	>22500	10	Throttle ability

Note: NR (Not Required)

7.1 Telecommunications

The purpose of this analysis is to identify the deficiency of existing EP equipment or EP systems under development as compared to the needs of future telecommunication satellites. Abundant information has been made available about existing EP technologies and plans for their future development; however, the analysis has to be based on a few assumptions. These assumptions take into account the current trends in satellite development with an extrapolation of communication satellite development into the future.

Expected communication satellite development

Electric propulsion will lower the mass of a telecommunication satellite bus considerably. This mass saving can be translated to additional payload or a cheaper launch. In reality a number of additional factors will influence the decisions of satellite primes and operators, the most important of which is overall cost. Again, the overall cost is depending on many factors, some of which can and will vary over the years, like e.g. the transponder revenues, launcher availability, dual launch capability, new launcher performances and price, interest rate at the financial market and others.
Today for operators the costs are broken down into :

- Satellite cost for 45-65% of total,
- Launch vehicle cost for 25-45%, and
- Insurance cost for 10%, with no impact of EOR option.

This present gap analysis can by no means take all of these factors into account. Market analyses should do this and are available. For the gap analysis presented here a number of simplifying assumptions are made:

- Telecom satellites in this analysis are solely geostationary satellites.
- Electric propulsion will be standard for station keeping manoeuvres.
- Electric propulsion for orbit raising/orbit topping will take an increasing share.
- Satellite launch mass (launcher capacity[1]) will not increase.
- Available power will increase only modestly (18-20 kW for the next 10 years).
- The satellite telecommunication market will support both high mass/high power satellites and more flexible smaller geostationary satellites.

Therefore the analysis is taking existing satellite lines or such already under development into consideration and tries to identify necessary steps in the development of electric propulsion technologies, which could be implemented and enable all electric/hybrid satellites in future.

Data base

To simplify the comparison a table is set up, which contains satellite data as well as EP technology data. The data for EP technology is taken from the report of EPIC D2.1 (RD4). The selection criteria applied are the following:

- Thrust > 10mN. This is a very low limit for station keeping of small geostationary satellites. The actual European SmallGEO series has already a higher demand.
- Available power ≤ 20 kW. This is the range of electric power available for orbit raising on the largest geostationary satellites actually under development. Solar power generation is assumed only.
- Isp higher than the limit for chemical propulsion. In special applications electric propulsion may be meaningful even at very low Isp (for instance Xenon resistojets or arcjets can share the propellant management system with the other EP thrusters thus avoiding the use of several propellants and corresponding tanks and as a consequence saving mass), and such technologies are therefore developed. For GEO satellites only the mass saving offered by the high Isp of EP systems is attractive.

Data for geostationary satellites is taken from RD4. Only European systems are included, because they cover the full range of launch masses or power availability.

[1] The recently adopted Ariane 6 program will provide Europe with launchers at competitive prices in two versions. The two-booster version Ariane 62 will be able to carry 5.8 tons into GTO, the 4-booster version Ariane 64 can lift 10.5 tons to GTO, a modest increase compared to the 9.7 ton lift capacity of the actual work horse, the Ariane 5 ECA. Both versions will have dual launch capacity; upper stage and payload fairing are identical. Dual launch on an Ariane 62 may become a very competitive launch option for all electric communication satellites.

		Launch	Bus	Mass / kg	Power / kW	Station keeping	Orbit raising	Transfer time	EP-System								
INFORMATION AVAILABLE FROM D2.2 ON NOV 4TH																	
Needs for ComSat	SGEO1/ HAG1	2015	SGEO Fast	< 3200	4,5	yes	-	n.a.	HET								
	SGEO2/ H2Sat	2019	SGEO Fast			NSSK	-	n.a.	HEMP / HET								
	SGEO3/ Electra OR		SGEO Flex	< 3000		yes	yes										
	GEO1 SES-12	2017	E3000	5300	19	yes	yes	3-6 months									
	GEO2 Eut172B	2017	E3000	3500	13	yes	yes	4 months									
	GEO3 Alphasat	2013	Alphabus	6650	12	NSSK	-	n.a.	HET								
	Classification	Performance Characteristics				Operational Characteristics				Integrability			Feasibility				
	Concept	Isp	T	Power/Thrust	Total Impulse	Cycles	Type of operation		Thrust Vectoring	Dry mass	Complexity	Thermal Loads	TRL	Time to TRL-5	Time to TRL-9	Development Cost	Recurrent Cost
	Unit	(s)	(mN)	(W/mN)	(MNs)		Throttable / operation points			(kg)	Qualitative	Qualitative					
ADDITIONAL INFORMATION FOR ANALYSES - GENERIC NEEDS FOR FUTURE MISSIONS																	
Low-power type mission		500 - 3000	1 -50	500	<1,5	20.000	Single mode ok		Useful, but not required								
Medium-power type mission		1000-2500	40	2.500-10.000	>1,5 & <10	Not critical	2 operating points: - Optimum T - Optimum Isp		Useful, simplifies mechanisms								
High-power type mission		3.000-6.000	1.5	10.000-50.000	>10	Not critical	Throttable		Useful, simplifies mechanisms								
INFORMATION FROM EP SYSTEMS																	
RIT10	GIE	3300	15	30	>1.5						☹		9		0		
RIT22	GIE	4200	50-200	35	>20		s. thrust range				☹		5	0			
T5	GIE	417-2926	0.6-20.6	32	>1.5		s. thrust range				☹		9		0		
T6	GIE	4180	75-145	35	>13,8		s. thrust range				☹		6	0			
T6 RC	GIE	3500	75-145	25			s. thrust range				☹		4				
PPS 1350-G	HET	1650		17	3.4						😐		9		0		
PPS 1350-E	HET	1670-1800	88-140	17	3.4		s. thrust range				😐		6	0			
PPS 5000	HET	2300-1750	230-325	15-20	15		s. thrust range				😐		4				
HT-100	HET	1000-1600	6-18	20	0.05		s. thrust range				😐		4				
HT-400	HET	1100-1900	20-50	20	0.2		s. thrust range				😐						
HT-5k	HET	1700-2800	150-350	22			s. thrust range				😐		4				
KLIMT	HET		10-30	20			s. thrust range				😐		4				
XR-5E	HET	1676-2020	117-290	15-18	>5.5		s. thrust range				😐		9		0		
HEMPT 3050	HEMPT	2000-3500	10-70	20-35	>4		s. thrust range				☺		6	0			
HEMPT 30250	HEMPT	2000-3500	30-330	20-35	>20		s. thrust range				☺		4				
SF-MPD	MPDT	10000	10k-70k	?			s. thrust range						2-3				
SF-MPD heated cathode	MPDT	2000	50k	?									2-3				
HPT	MPDT	<2500	<14k	?									2-3				
AF-MPDT	MPDT	2500	2000	?									2-3				
AF MPD ZT1	MPDT	3000	250	40									3				
QCT-1500	QCT	1600	10	72					Yes				2-3				
ATOS	Arcjet	480	115	7	0.4								9		0		
AT-1k	Arcjet	590	>125	3-8									3-4				
MR-501	Arcjet	585-615	222-258	9	1,45		s. thrust range						9		0		
HPT	Helicon	1009	1480	10.1									2-3				
TITHUS	Hybrid DC/RF		2000										2-3				

Additional considerations

Additional considerations were analysed in detail in RD5 but are recalled and summarised hereafter for clarity of the analysis.

<u>Orbit raising, thrust per power:</u> For orbit raising, the thrust of EP systems shall be high enough to allow the transfer of a satellite into GSO within reasonable time. In this context the power-to-thrust ratio is becoming important. Assumed that EP systems could be scaled such as to fully exploit the electric power offered by the platform, then the transfer time will depend on the power-to-thrust ratio of the EP system. This is illustrated in Figure 7-1 below. The solid and the dashed lines correspond to the power efficiency of the EP system with the bold solid line representing the theoretical limit of 100%. For comparison, the practical Isp limit of chemical propulsion is indicated by the red vertical line. The optimum EP system would have a high thrust-to-power ratio, so that transfer time is relatively short. Therefore, for orbit raising the key parameter is the high thrust-to-power ratio, and the high Isp is desirable but not required for orbit raising as long as it is significantly higher than for chemical propulsion to benefit from the mass savings. The range for EP systems with a useful set of parameters is highlighted in red. Figure 7-1 also contains the relevant parameters of a number of existing European EP systems. The region of optimum thrust/power vs. Isp is only sparsely filled. It should be noted that the

absolute power that one of these thrusters can handle is not visible in the plot. In Figure 7-2 Isp is plotted against available satellite power. For orbit raising the range of useful systems is defined by minimal and maximum available power (2 kW -20 kW) vs. Isp in the range 1100 s – 4200 s. The Isp range reflects the Isp targets of Figure 7-1.

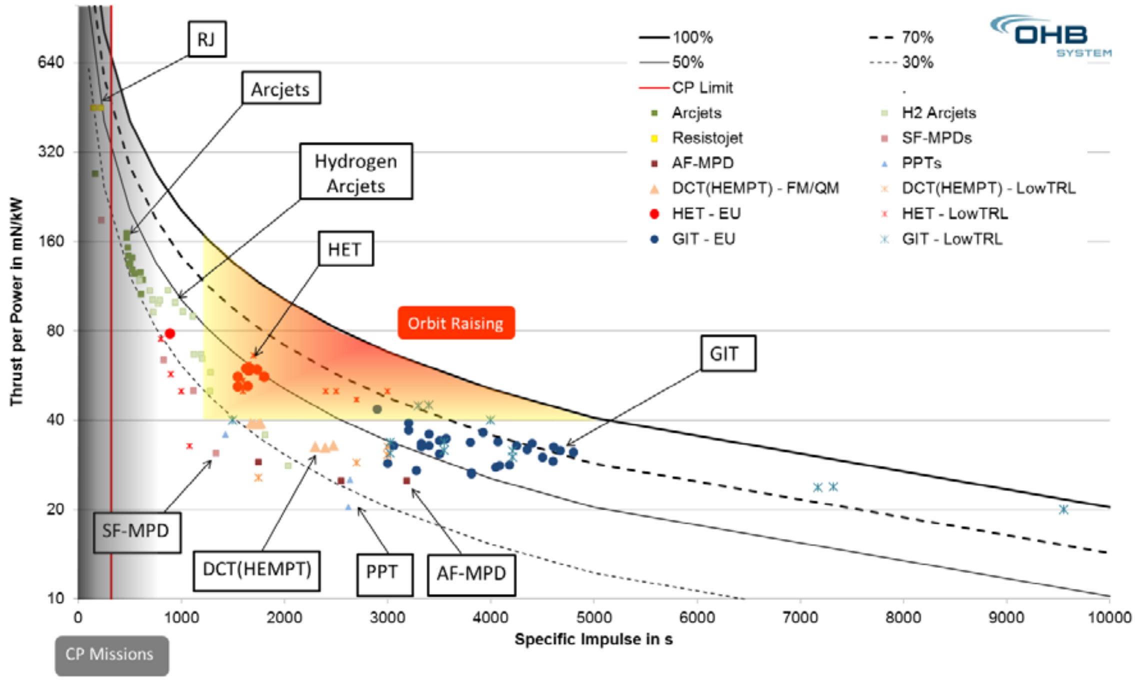

Figure 7-1: Existing thruster technologies surround the optimum Isp vs T/P region for orbit raising (RD8: OHB Courtesy)

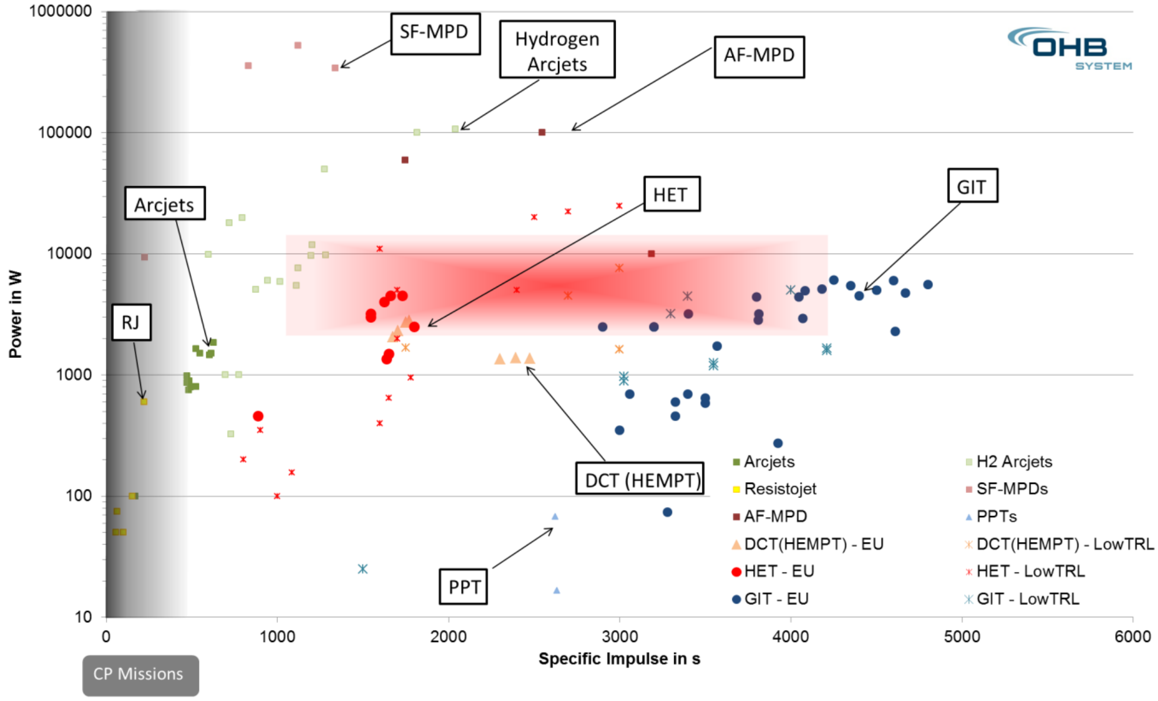

Figure 7-2: Orbit raising of geostationary satellites with current EP technologies (RD8: OHB courtesy)

Direct injection, station keeping only: For station keeping operations, the Isp is more important than thrust, because the time for the operation is less critical. For the selection of thruster technology the scenery can change completely, if e.g. the launcher allows direct injection. This depends on the business model of the satellite operator, who may prefer not to use the mass savings due to EP for additional payload, but rather for cost saving by a smaller launcher or an early start of operation by using a launcher with direct injection capability. In this case a thruster technology, which offers highest Isp at a modest thrust-to-power ratio would offer the highest mass savings and thus the easiest access to the GSO position.
Figure 7-3 is a plot of thrust–to-power ratio over specific impulse. In the station keeping case the target range for power-to-thrust ratios is extended. Also Isp values in a very broad range from nearly 1000 s to well beyond 5000 s may be useful. This target range is highlighted in green in the figure.
Also for the station keeping case a number of existing European EP systems are displayed in the same figure. For a number of thrusters test data at different operational points has been published in the literature, and many of these numerous parameter sets are included in the figure. In this case a number of thrusters fall into the useful range, but also in this case there is room for improvement. This is more clearly seen in Figure 7-4, where power in a reduced range from 1 kW to 3 kW vs. Isp is displayed.

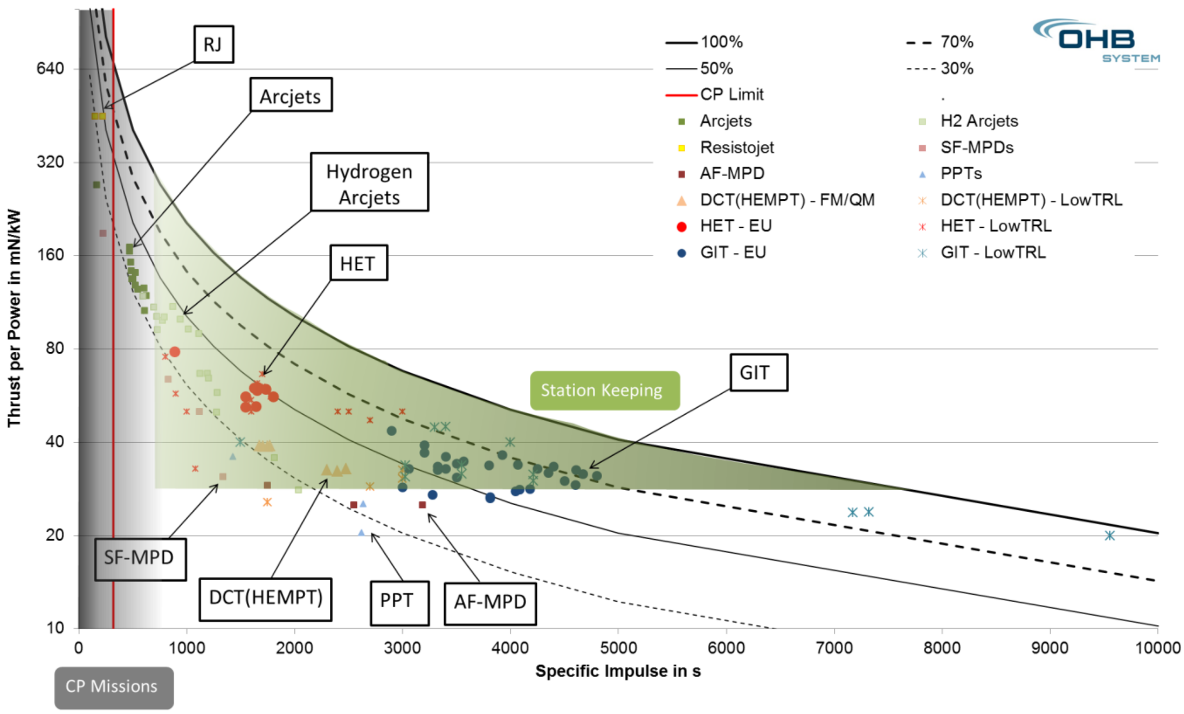

Figure 7-3: Desired ISP and thrust per power ratio for station keeping (RD8: OHB courtesy)

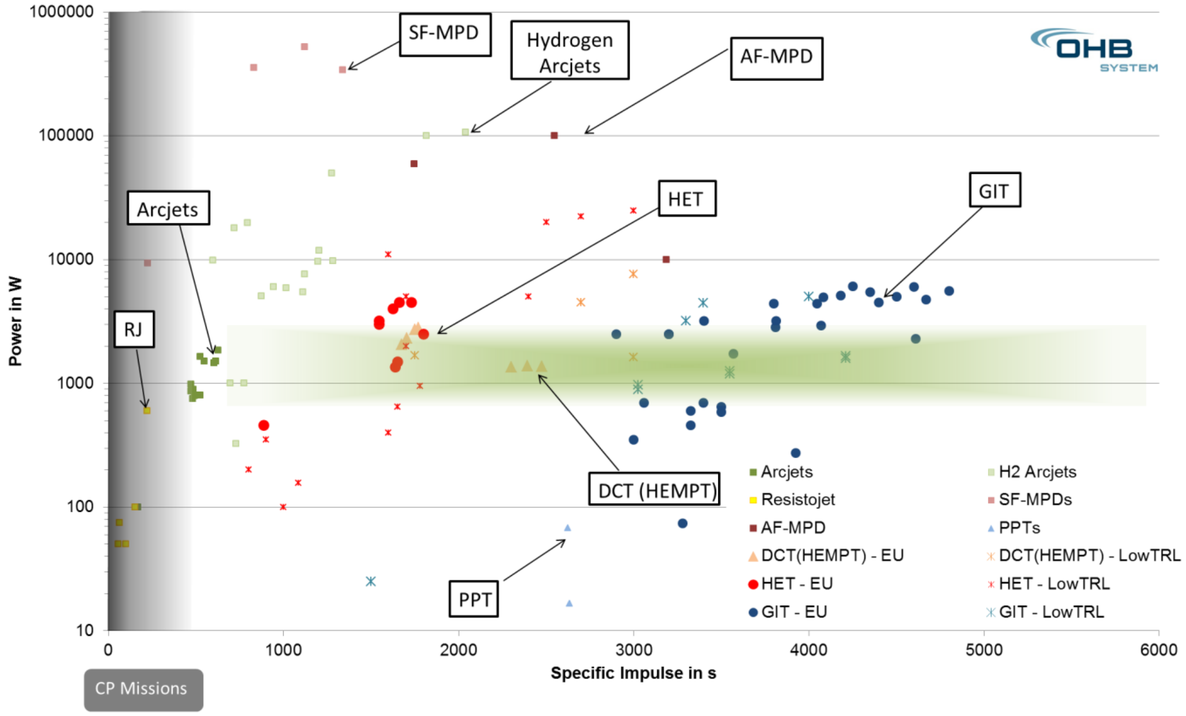

Figure 7-4: Power vs. Isp for station keeping of geostationary satellites with current European EP technologies (RD8: OHB courtesy)

Cost, complexity, and power supply: For the final decision of a satellite prime, which EP system to implement for orbit raising and/or station keeping, additional factors are taken into account. As stated already, the overall cost will remain to be the most important factor. This includes the price for the thruster, but as well the one of the other subsystems such as the power processing unit, and the thrust orientation mechanism subsystem. The last two components normally are the more expensive part of the EP system: the PPU can cover up to 50% of the entire system cost and the thrust orientation mechanism about 30-40 %. Therefore the development of power processing units towards higher power and lower cost has to be considered at the same time. Both trends are under development and 5 kW PPUs are within reach, but industrialization and cost reduction for PPUs has just started and TRL is still low.
It has to be noted that different thruster technologies may have different requirements. For example, GIE require several high voltages, whereas HEMP thrusters only need one. In order to use PPU modules efficiently in redundancy and thrust vectoring/directing schemes most the EP-concepts require switching of high voltage lines between PPU and thrusters. Orbit raising and station keeping operations with the same thruster will be optimised when dual mode operation of the thruster will be possible as this is the case for US and Russian thrusters. In that case the PPU must be able to switch between these different voltages as well.

When selecting the propulsion system for a future telecom satellite, additional consideration will be given to system complexity and cost of integration. The choice of thrust steering and the trade-offs between different methods such as mechanisms or multiple thrusters is one of them. Indeed, the objective of the thrust steering is to maximise the thrust through the spacecraft centre of mass in the direction of motion, the design of the integration into the satellite is an important aspect of this trade-off. For orbit raising lower Isp thrusters with wider plume angles have tended to be restricted to up to 45 ° separation between the thrust vector and the required direction of motion thus efficiently reducing the thrust by 30% of the thrust generated. Higher Isp engine with 15 ° plume widths can in principle generate up to 97 % of the generated thrust in the required direction. Extending boom or arms can help to overcome the wide plume problem but for higher power thrusters the very heavy harnesses can be a significant disadvantage. Similar arguments may also be part of a multiple-thruster approach. The competitive and optimal solution can only be found by detailed trade-offs studies with real systems, real satellites and a balanced consideration of all the issues.

Conclusion

For orbit raising the three established technologies HET, GIE, and HEMP-T seem to be the most promising, but none of them is in the optimum range yet. GIE offer a high Isp and a good relative energy efficiency, but thrust and thrust-to-power ratio are too low. Hall Effect Thrusters are worse in relative energy efficiency, but can deliver higher thrust and thrust-to-power ratio. Their Isp is at the lower edge of the optimum range. The HEMP technology is somewhere in the middle, with a good Isp, but its thrust-to-power ratio requires much improvement. Models of all three technologies exist, with performance figures more in the optimum range, but there TRL is still low.
Other EP technologies in Figure 7-1 and Figure 7-2 are either far too low in Isp, like arcjets or resitojets, or have an insufficient thrust-to-power ratio, like PPTs. This is also true for the thruster examples in the table other than HET, GIE, and HEMP, which have passed the above mentioned selection criteria. Most of them have a very low TRL, and the two arcjets with TRL 9 offer a Isp improvement by a factor of 2 compared to chemical thrusters.
In the station keeping case the useful range is much broader, nevertheless the same technologies as for orbit raising seem to be best suited. This can best be seen in Figure 7-4. But it is also apparent that none of the existing thrusters is in the sweet spot yet. The HETs, which are most commonly used today for station keeping on European satellites, have an Isp at the lower edge of the useful range. HEMP thrusters are better in this respect, but there TRL is still lower. The low thrust to power ratio is not so critical in the station keeping case. GIEs offer a nice Isp, which is most important for station keeping applications, but they may be a bit low in thrust-to-power ratio mazinly for orbit raising, and the models under development, which promise to overcome this weakness, have again a low TRL.

To make full use of the entire power availabale on-board future Telecommunication platform, the opportunity and ambition to develop higher power EP systems (10 kW) shall be taken. Today European manufacturers are developping 5 kW thruster based EP system which can also be clustered to fulfill this objective. However a lot of impacts on the host system (interactions, mass penalties, etc) shall be investigated, which can be at the benefit of using only one higher power thruster. The dual mode operation (i.e. using high Isp/low thrust and low Isp/high thrust for the different mission phases) shall be also baseline for those new thrusters.

Power Processing Units (PPU) are a significant cost driver and can make easily half of the development cost and recurring cost of an EP subsystem. European PPU's at high TRL (8-9) level are currently only available at 1.5 kW and 2.5 kW power for HET, and at 2*1.4 kW for HEMPT - ready-to-market for telecom. However, all these products may need, for instance, a further iteration of industrialization to improve their cost competitiveness including impact of need for a delta-qualification. Today, addressing higher power needs for orbit raising this would require clustering of units with compatible thrusters.
For GIE 6.8 kW PPUs based on 5 high power modules are available for science missions at TRL8, but only TRL 5 for telecom (here 5.1 kW by 4 modules). Capabilities to supply 5 kW class of thrusters is targeted by several European PPU suppliers expected to be achieved at TRL 8-9 level within the next 2-3 years. It has to be mentioned, that all these new near term developments for higher power will end up with a first result, which typically needs a further cycle of industrialization, which duration can be 3-5 years year in addition to improve cost. Furthermore, the first 5 kW class thrusters is/will be supplied by PPUs, which generate the high power out of parallelized high power modules, where the block size is in the order of 2.5 kW, however a bock size of 5 kW would allow further mass and cost optimization. Multiple-operation (variable/configurable working points) has not been specially addressed today, although it might be useful in the future to address variable working points of thrusters and to adjust to missions. Furthermore, todays PPU allow limited range of adaptation to different thruster. The increase of modularisation of PPU is a trend which is expected to help for cost improvement. There is also the expectation that new types of electrical components (semiconductors), materials (PCB's) and processes (packaging) may help to improve the power per module capabilities and/or provide cost reduction. PPUs for GIE in the low power class around 500 W have been built and achieved TRL 9, however have never been reproduced and can be considered as out-dated for the high competitive telecom market.
Direct drive concepts are often mentioned in context with reduction of high PPU cost as the expectation is to eliminate or simplifier a part of the PPU, the PPU could be even merged with the Power Control Unit of the spacecraft bus. For telecom the impact on the spacecraft power bus architecture and the non-availability of high voltage solar arrays does not make this solution very attractive, however overall systems concepts for future have not been studied in detail up to now.

Finally, with EP there is normally a trade-off to be performed between power required, propellant available and time. In the telecommunication sector, to achieve maximum competitiveness, operators need the greatest flexibility on these trade-offs. Cost, drymass and complexity are also important factors but only in how they affect the best financial solution to meet the mission requirements.

7.2 LEO

7.2.1 Earth Observation and constellations

The success of the ion engine in the GOCE spacecraft for drag compensation purposes has demonstrated the potential of this technology for fine control of satellites flying in LEO.
A new post-GOCE mission is being designed at ESA: Next Generation Gravity Mission (NGGM) for monitoring the variations of the Earth Gravity field. This mission is composed of two small satellites flying in formation in a very low orbit. Micro-Newton cold gas thrusters and mini-ion engines are being considered for compensation of the very small cross track drag forces; thrust range between 50 and 2500 µN with a resolution of 1 µN in the lower range is required. Both technologies are available in Europe. However, the micro cold gas propulsion system is already flying on-board the ESA GAIA mission, being an advantage for a better consideration on future platforms. EP can perfectly compete and even improve the performance of the propulsion system increasing the reduction of the noise, and with a much higher specific impulse, reducing the amount of propellant to be embarked on the spacecraft or allowing to increase the mission duration. The mini-ion engine EP system is today at TRL 4 and should be qualified to be able to be considered for future applications. A µN HEMP-T development has also been started for the same purpose, but TRL is still very low. These flying formation missions in Earth Observation have similar requirements to science missions such as e-LISA or Darwin, thus the thrusters required for this kind of missions are similar.

Finally, a number of feasibility studies and preliminary mission analysis have been and are still being carried out for Earth observation applications, based on the use of low-power HETs on small (400 kg-class) to medium (1.5 t-class) satellites. Namely, it has been shown that future high resolution missions could benefit from this type of technology, through a broader range of accessible orbits (from 480 km up to 830 km altitude) while being compatible with a VEGA launcher. Besides, low-cost scientific or Earth observation missions on small satellites (400 kg-class) at very low altitude (below 300 km) have been studied for different scenarios that are all made possible by the use of electric propulsion.

Moreover the recent announcement of a project for an internet constellation has raised the interest of EP for small spacecraft to be built in enormous quantity (industrialisation level) at very low cost for station keeping operations. European providers are developing small, integrated and low power HET based EP system, with a power range of 200-700 W that could be fit for the purpose. Existing gridded ion engines in the 20-40 mN thrust range (like the T5 ion thruster which is at TRL 9) would also do the job allowing saving propellant thanks to its bigger Isp wrt HET. The main known issue for low power HET is lifetime, which is today limited to about 1000 hours of operation. And to be able to compete worldwide for this new market, a great effort in cost reduction of the entire EP system shall me made (Space X intends to buy the EP system to put on its constellation for $12500).
The same thrusters used for LEO constellation missions would also be beneficial for Space debris removal purposes.

Power Processing Units (PPU) cost of an EP subsystems are currently available at high TRL for small power HET and for FEEP. PPU's for GIE in the low power class around 500 W have been build and achieved TRL 9, however have never been reproduced and can be considered as out-dated for the high competitive telecom market. For small satellites they need to be optimized in overall power consumption, sometimes have to consider tailored mass and size budgets. Configurable PPU solutions and flexible building blocks may help to keep the mission specific PPU cost low.
Direct drive concepts appear not to be a solution for LEO low power missions as typically their high power solar array not fitting in a low power satellite bus concept.

7.2.2 CubeSats

The Cubesat and Nanosat market are an emerging market which is taking more and more importance in Space applications. Numerous EP micro-propulsion systems are currently in development and qualification in Europe for being used on those satellites. When available and flight qualified, these propulsion systems will enable CubeSats and Nanosats to manoeuvre for the first time and thus significantly increase the mission utility and flexibility.

One of those EPS is a Pulsed Plasma Thruster (PPT) system specifically designed and developed in collaboration with ESA for use on CubeSat platforms for attitude and orbit control applications. Two different thruster systems have been developed with different thrust levels. PPTCUP (34 µN, thrust-to-power ration 17 µN/W, Isp of 560 s) is soon to undergo qualification, including life and EMC testing, and the first flight unit is planned to fly on the SAMSON mission from Technion, Israel, in 2015. The higher thrust version occupies a 1-unit CubeSat volume, delivers a thrust of 80 µN for a power of 4 W and a total impulse of 150 s.

A Micro-Colloid thruster system was developed, in the frame of a EC FP7 project, by the Microthrust European consortium. The system is packaged in a 60 g propulsion module including several micro-emitter arrays for the electrospray atomisation and a microfluidic propellant storage and feed system. The module delivers a thrust of 0.3-0.6 mN at a specific impulse of 3000 s, thus providing a total delta-V capability to satellite of more than 500 m/s. A prototype was realised and was tested for a few hours in laboratory conditions.

A FEEP system is also being developed for CubeSats using ionic liquids (principally EMIM-BF4) instead of Cesium as the propellant. The specific impulse is estimated around 3000 s with a thrust of 0.1 mN at 4 W power input. Furthermore the IL-FEEP development is funded under EU (FP7 E-sail) and ESA programmes.

PPUs seem not have been materialized as self-standing product for Cubesats up to now as they are typically kept simple and well integrated with the thruster and satellite.

7.3 MEO/ Navigation

The Galileo 2G programme, with the European Union (EU) as main customer/user, is targeting the possibility to increase the Galileo Payload capability without impacting the launch costs (and possibly reducing them). The need to increase the size of the Galileo payload (mass and power) is deriving from system needs, which are considered to become essential in a new scenario of Galileo, starting in 2020 and having its final configuration not earlier than 2030.
To increase the payload capability an option is to change the launch injection strategy in combination with the use of EP for orbit raising from the injection orbit to the target operational orbit.
In the frame of this programme, development of 5 kW engines and their associated system have been initiated and are on-going: mainly the PPS®5000, the T6 and the XR-5E HET. The ultimate selection of the EP system will be based on the need to provide adequate thrust to achieve mission objectives, to maximise the specific impulse and to reduce the subsystem power demand. In addition, cost and industrialisation status will be a strong driver for the selection.

PPU have been considered in the above mentioned study focussing on improving the industrialization to bring down recurrent cost. In principle the PPU related conclusion in chapter 7.1 are valid here as well, starting point are here the high power developments of industry.
More generally it should be noted that any development initiated or pushed for the telecommunication market will directly benefit the ones for MEO missions.

7.4 Interplanetary/Science

Science missions span a huge range of propulsion requirements. Earth observation missions normally use low Earth orbit (see section 7.2.1 above) and the special requirements include continuous low thrust for drag compensation, high-precision thrust for exact spacecraft pointing or relative positioning in case of formation flying satellites. For interplanetary or space science missions propulsion requirements can be as different as very high thrust engines to enable large Delta-V for the long journey or low thrust high Isp engines for orbit maintenance manoeuvres during the orbit around the Sun Earth Lagrange points. Three out of the six missions in the ESA Cosmic Vision Program 2015-2025 are missions to the second Sun-Earth Lagrange point, L2. Sample return missions from asteroids or other celestial bodies have their very special requirements like high thrust as well as high Isp.

Today most of the mission analysis studies for interplanetary and exploration missions are based on already existing or in development thrusters (≤ 5 kW thrusters). It can be expected that any new EP system and disruptive technologies considering very large total impulse, high thrust and large throttleability with high specific impulse will be considered for missions in this domain and as already said maybe ambitious mission enabler.

7.4.1 Exploration missions

Exploration missions have specific performance requirements, and in particular, future missions may require higher specific impulse and total impulse levels currently only available with ion engines. Availability of very-high-power HET and/or GIE systems will enhance future robotic exploration missions. Such system will provide remarkable mass gain, which can be converted into either additional payload or a reduced launch mass, with acceptable transfer duration. Pre-development activities on 10 kW and 20 kW EP systems have already been performed with ESA, EU and National funding. Magneto Plasma Dynamics (MPD) thrusters, although in their early development phase, could enhance such missions even further. Furthermore, emerging technologies such as the Helicon Plasma thrusters (HPT), Quad Confinement Thrusters (QCT) and Electron Cyclotron resonance (ECR) thrusters are currently being developed in Europe. HPTs are also being developed under EC funding and under ESA GSP. QCT is in development under the NSTP UK national programme. ECR thrusters are in development under the Neosat programme.

Power Processing Units (PPU's) based on the SMART-1 are available for HET up to 1.5 kW at high TRL (9) and based on BepiColombo mission for GIE up to 6.8 kW (using 5 high power modules) at TRL 8. The trend towards higher power goes in line with telecom market development and the related PPU developments. In the future the use of thrusters with high(er) Isp may either involve higher voltage levels or higher current level - higher than today. For the emerging thruster no PPUs have been studied up to now for space application. These may need power source quite different from the existing developments.
Direct drive concepts may make sense for exploration missions with EP as the spacecraft power system is anyway then dedicated to supply the EP system and could allow therefore simplification of PPU and PSCU architecture, presuming that the feasibility of high voltage solar arrays is given.

Moreover Exploration missions are long duration missions which require an enormous amount of propellant to be embarked on the spacecraft. Currently the availability of the usual propellant used in EP (xenon) is not an issue but the price is becoming a bit part of the mission budget (about 1500 euros per kg). Therefore as for Space transportation missions the investigations on finding alternative propellants or being able to use non-conventional propellants (i.e gases found in the atmosphere of the visited planet, etc.) are becoming increasingly important. In that case the existing EP systems (mainly HET, GIE and HEMPT) may need to be optimised to be used with those new gases. Any disruptive thruster may take this consideration into account already in the very first development phases (design).

7.4.2 Scientific missions

A large panel of European thrusters are being developed to fulfil the requirements for scientific missions but are still at low TRL for most of them and as such still miss flight heritage.
EP for European science missions has had to push performance to new limits and has consequently had high development costs. This has given a perception of high risk and high cost. Combined with a reluctance to re-use developed technology this has given EP a bad name in Europe in contrast to the US, Japan and Russia.

FEEP thrusters is a potential candidate for scientific ESA missions such as e-LISA and have been developed by ESA to accomplish specific attitude control tasks requiring a fine thrust modulation at very low thrust noise level with a very high specific impulse. These thrusters provide micro-Newton thrust levels with an accuracy of less than one micro-Newton.
Miniaturised versions of Ion Engines (mini-Ion Engine) are currently available at engineering level. The qualification of such thruster will enable drag free and formation flying conditions.
A µN HEMP-T development has also been started for the same purpose, but TRL is still very low.

Power Processing Units (PPU) for science missions are currently available at high TRL for low power HET and for FEEP. For small satellites they need to be optimized in overall power consumption, sometimes have to consider tailored mass

and size budgets. Configurable PPU solutions and flexible building blocks may help to keep the mission specific PPU cost low.
Direct drive concepts appear not to be a solution for low power science missions as typically their high power solar arrays are not fitting in a low power satellite bus concept.

Flow control units (FCU) for µN thrust propulsion systems are a very challenging development task. MEMS based FCUs seem to be promising candidates, but TRL is still low. Proportional valves able to regulate such minimal mass flows with the required accuracy will be bulky and no European ITAR-free system is above the horizon. On-off valve systems may be a way out if they can prove the necessary high cycle lifetime and low gas pressure ripple.

7.5 Space Transportation

Based on growing maturation of Electric Propulsion Systems and increasing capabilities of such propulsion devices (power rising), possible applications to space transportation vehicles have gradually been studied with a more and more detailed level of analysis and have been reported in detail in RD5. Those potentially new platforms would be able to provide power above 20 kW to the propulsion system if needed.

Like for Exploration, most analyses have been performed with existing thrusters (mainly 5 kW) showing the need to cluster them to be able to comply with the high thrust requirements (above 2 N).
The overview presented in RD5 for the Space Transportation domain of the different type of missions demonstrated an important potential for EPSs for future missions. The already promising results would be greatly improved if more powerful engines were available. It is the reason why such potential applications are looking for more powerful electric thrusters to limit the number of engines to be assembled in a cluster. No such thruster (20 kW) is available in Europe or only at very low TRL (2) but will need to be developed to enable this new application domain for EP.

Moreover for this kind of mission with several journeys the quantity of propellant to be embarked will be a non-negligible part (several tens of tons) of the satellite mass. Therefore new development for propellant storage (cryotanks, new material, lighter materials, for instance) shall be envisaged to allow considering this application as a future credible market.

For PPUs used in space transportation in principle the similar conclusion are valid as for telecom (see chapter 7.1). High power PPUs at low recurring cost are required in a strongly competitive market environment.
Power Processing Units (PPU) are a significant cost drivers and can make easily half of the development cost and recurring cost of an EP subsystem. European PPU's at high TRL (8-9) level are currently only available at 1.5 kW and 2.5 kW power for HET, and at 2*1.4 kW for HEMPT . However all these products may need a further iteration of industrialization to improve their cost competitiveness including impact of delta-qualification. Addressing higher power needed for orbit raising would require clustering of units with compatible thrusters. For GIE 6.8 kW based on 5 high power modules are available for science missions at TRL 8, but only TRL 5 for telecom (here 5.1 kW by 4 modules). Capabilities to supply 5 kW class of thrusters is targeted by several European PPU suppliers expected to be achieved within the next 2-3 years. It has to be mentioned, that all these new near term developments for higher power will end up with a first result, which typically needs a further cycle of industrialization, which duration can be 3-5 years year in addition to improve cost. Furthermore the first 5 kW class thrusters is/will be supplied by PPU which generate the high power out of parallelized high power modules, where the block size is in the order of 2.5 kW, however a bock size of 5 kW would allow further mass and cost optimization. Multiple-operation (variable/configurable working points) has not been specially addressed today. Furthermore, todays PPU allow only limited range of adaptation to different thruster. The increase of modularisation of PPU is a trend which is expected to help for cost improvement. There is also the expectation that new types of electrical components (semiconductors), materials (PCB's) and processes (packaging) may help to improve the power per module capabilities and/or provide cost reduction. Direct drive concepts may make sense for space transportation with EP as the spacecraft power system is anyway then dedicated to supply the EP system and could allow therefore simplification of PPU and PSCU architecture, presuming that the availability of high voltage solar arrays is given.

As a summary final goal is to get a clear identification /validation of the capabilities of the existing concepts, to identify their limitations and to build a work plan for high power (> 20 kW) conditions.
Lessons learnt from the ISS could be useful for this kind of applications for the management of heavy platforms, very high power and associated high voltages.

8 EPS SHORT TERM NEEDS

It is important to have a clear view of the short term needs, i.e. the developments to be performed in the next 3 to 5 years (at ESA and National Agencies level), in the field of EP in Europe, to have competitive products for the main markets which are Telecommunication, Navigation and LEO missions.
Based on the previous analysis and on the actual trend and technology state-of-the-art (RD4), one can highlight the short term needs for electric propulsion systems:

1. For telecommunication: platforms which have a significant increase of power payloads on board, requiring high power generation systems. This additional power is available for orbit topping using EP. The current trend is to develop all-electric propulsion platforms. In the most evolutionary concept the platform will not make use of chemical propulsion systems on board for GTO transfer. Therefore the need is to continue the development of EP systems (high power 5 kW range thrusters or cluster of lower power thrusters) capable to provide a very high total impulse capability and able to work at different power levels because of the multiple tasks required for orbit insertion and orbit maintenance. As a next step, thrusters should be able to operate at different thrust or Isp values, thus favouring high thrust for EOR, and high Isp for station keeping, which is often referred to as "dual-mode" capability.
2. For LEO applications for Earth science and observation: micro-Newton range EP thrusters will enable drag free and formation flying condition while low power EPS will allow drag compensation and disposal at end of life.
3. For exploration: EP systems above 20 kW would anticipate the high power (solar or nuclear) availability and keep the pace with US advances in this range.
4. For space transportation: main issues are high thrust, long duration, low cost and reliability. Synergies can be found with points 1. and 3. above.

This translates in the following developments already identified in RD1:

- Development and qualification of thrusters and related components/subsystems (5 kW range) with higher total impulse capability, high modularity and operational flexibility (e.g. with dual-mode operation), and design to reduce the costs (competitiveness).
- Development and qualification of PPU (5 kW range) with high modularity, operational flexibility, and design to reduce the costs (competitiveness).
- For scientific mission and small platforms: the accomplishment of qualification of micro and mini Electric Propulsion systems (in progress for some of them) and the in-flight demonstration of those systems. This includes very low power EP systems (<200 W) which are useful for small satellites and have a greater opportunity for flight demonstration and application due to the small satellite/s expanding market.

Furthermore, to be competitive (in terms of performance and costs), the complete EP system should have the following characteristics:

- Operational flexibility, autonomy and reliability:
  - High performance of the EP system to maximise the efficient use of satellite resources (propellant mass, electrical power, dry mass and volume);

- Extended total impulse capability and modularity of operation (dual-mode operation) for mission optimisation and trouble- shooting if needed;
- Increase EP autonomy to minimise ground control costs: assessing how at system and EP sub-system level the autonomy can be increased for EP use for long duration missions
- Allow low-complexity EP system operation for robust, autonomous space mission operation over long durations (reducing operational cost to customers);
- Allow operations with cluster architecture to increase reliability for high power demanding missions.
- Evaluate potential interferences with payloads and study possible counter measurements.

- Competitiveness:
    - Improve the access price to overall electric propulsion systems, where consolidated products are available by European suppliers, to be competitive with American (Aerojet) and Russian (Fakel) solutions in particular;
    - Increase the competitiveness of the current European products (HETs, GIEs, HEMPTs, FEEPs, etc.). In this process the qualification of the EP products is one of the main needs;
    - Increase the competitiveness of pressure regulators or suppress the need for such an equipment altogether, by developing flow controllers compatible with high inlet pressure;
    - Achieve a maximum penetration of different markets such that a high number of subsystems can be produced allowing reduced EP subsystem cost to customer and independence of market volatility;
    - Reduce the cost of EP for small satellite applications;
  - Reduce solar arrays cost:
    - o low cost solar arrays devices,
    - o high voltage solar arrays concepts to decrease the cost of the PPU.
  - Reduce PPU cost as a significant cost driver of EP-systems ;
    - o by high degree of industrialization including simplification of design, EEE-parts count reductions and manufacturing process optimisations,
    - o modularity (use of standard building blocks for the different PPU functions and power outlets),
    - o flexible concepts adjustable to different EP thrusters;
  - High power range of PPU (e.g. power handled per conversion block is currently at 2.5 kW, increase to 5 kW in med-term an 10 kW in long-term needed).
- Need of research on new materials to improve lifetime of thrusters (material selection and characterisation).
- Components:
  - Increase of ITAR free parts to allow European non-dependence and to provide a cost neutral solution and double source for critical components of EP systems.
  - Consider the use of MEMS components in order to increase competitiveness by decreasing mass, volume and power of the different subsystems.
  - New generation of pressure transducers.
- In the commercial market the volume of EP systems produced will be high due to the very nature of the field. However, in the scientific arena there are fewer missions and they usually require a higher level of sophistication: synergies between these projects and the commercial sector should be sought after.

- Propellants:
  - Need of extended research on alternative propellants to xenon (e.g., argon, Krypton, or gas mixtures containing xenon). Indeed the supply of xenon in the future can become an issue, in terms of price and/or availability. The investigations should first be at system level (and not only thruster), so as to investigate their interest for satellite applications.
  - Need to pursue studies on non-conventional propellants (O_2, N_2, etc.).
- Test facilities and diagnostics:
  - Need of a sufficient amount of dedicated test facilities and standardization of test procedures to accomplish a successful development and qualification of the electric propulsion systems, including EMI.
  - Performance measurement to common baseline/standards is required (e.g. ISO 17025) to give the full transparency in assumptions, calculations and measurements.
  - Need of experiments for understanding of physical processes in EP plasmas for development and validation of numerical models, codes and tools.
  - Development of a European certified calibration facility for diagnostics and probes. Each large facility in Europe is significantly different, and whilst there may be some perception that common procedures can be implemented, it is unlikely that facility diagnostics can be standardised in a cost-efficient way.
  - Promotion of a European network of EP test facilities.
- Modelling tools:
  - Understanding of thruster and cathode physics.
  - EP thrusters/spacecraft interactions (modelling and experiments): due to the important future of EP systems on-board new platforms and satellite, the necessity to have dedicated system analysis models/tools for plume/plasma, interaction of RF/ plasma and erosion is becoming crucial. Those models shall also be validated by experimental campaigns with dedicated equipment. Results of such models will also be used to optimise location of propulsive devices in the spacecraft to limit pollution and deposit around the plume
  - Need to develop plasma probes to allow in-orbit validation of theoretical models built on ground.

9 EPS MEDIUM AND LONG TERM NEEDS AND GAPS

The EC H2020 program and its future SRC have the objective to develop competitive EP products and increase the exploitation of space systems within the 2020- 2030 timeframe. Major advances and strong innovation in EP shall be enabled for in-space operations and transportations in order to contribute to guarantee the leadership of European capabilities in electric propulsion at world level.

The following future trends are expected:

- ≥ 20 kW communications and navigation spacecraft orbit raising and station keeping
- > 20 kW space transportation systems for orbit transfer, interplanetary propulsion and debris removal
- >> 15 kW science and exploration missions requiring very high thrust and/or very high specific impulse
- Nano and micro satellites
- New technology and system concepts in power generation, distribution and conditioning
- Innovative micro-propulsion techniques for very small agile satellites operating in constellations.

Therefore, and based on the technology state of the art as well as the requirements derived from RD5 and RD8, the long terms needs in EP systems are presented hereafter. Identifying the gaps for each application domain allows to identify the characteristics of the future EP systems that shall be developed to be competitive and ready to respond to any changes in the markets and future strategic opportunities.

The following gaps were identified per application domain:

- Telecommunication and navigation (MEO)
  - Dual mode operation
  - High power operation (thruster and PPU)
  - Alternative propellants to xenon
  - Increase of lifetime or Total impulse
  - Innovative and cheaper PPU concept
  - Faster Electric Orbit raising capabilities
  - Improvement of the fluidic architecture (simplification)
  - Overall launch mass savings
- Space Transportation
  - High power operation (thruster and PPU)
  - Alternative propellants to xenon
  - Direct drive concept
  - Increase of Total Impulse
  - High efficiency solar arrays
- LEO
  - Optimised (in terms of performance and costs) of the EPS for the respective applications
- Exploration/Interplanetary/Science
  - Increase of lifetime
  - Alternative propellants to xenon
  - High power operation (thruster and PPU)
  - Low power/ microthrust capabilities.

The generic needs for the long term are:

- reduction of cost per transponder
- reduction of time to orbit
- satellite system compatibility
- multi-launcher compatibility
- sub-system cost reduction
- improvement of operational constraints
- decrease of xenon consumption
- extension of the mission duration
- cost reduction (main contributor being the PPU)
- increase of reliability and autonomy
- standardisation of PPU (multi-thrusters and multi-thruster technology compatibility)
- modularity of PPU
- non-dependence of EP components (e.g. avoid ITAR restrictions)
- innovative power supply design and architecture: different voltages, direct drive, different modelling tools
- need of breakthrough power supply technologies, optimization of mission strategy, and new propulsion technologies.

In addition to the characteristics defined previously for the short term and the general characteristics presented above, the main long term needs by technology are the following ones:

Hall Effect Thruster SYSTEMS (future technology improvements)

- High voltage operation (high specific impulse)
- High power ($\geq$ 10 kW)
- Throttleability
- Alternative propellants
- Clustered or multi-channel configurations

- Increased total impulse
- Direct drive
- Double operation points
- Low power (200 – 800 W) integrated EPS
- Innovative and cheaper PPU
- Industrialization

ION ENGINE SYSTEMS (future technology improvements)

- High power (≥ 10 kW) with high specific impulse
- Reduction of power-to-thrust ratio
- double operation points
- Increased lifetime
- Low power ion engines for formation flying and drag compensation.
- High throttleability
- Alternative propellants
- Industrialization
- Innovative and cheaper PPU

HEMPT SYSTEMS (future technology improvements)

- High power (≥ 10 kW)
- Dual mode operation
- µN HEMPT for future science mission
- Alternative propellants Industrialisation
- Innovative and cheaper PPU

Other EP thrusters, New EP Concepts, Components, Test Facilities, Modelling, PPU New Concepts, Power Sources

- Micropropulsion (FEEPs, micro-PPTs, MEMS colloids, etc.)
  - Performance improvements (lifetime, noise, specific impulse, thrust range, etc.)
  - Qualification of the EP system
  - Compact system
  - Industrialisation
  - Cost reduction
- Cathodeless propulsion:
  - Helicon Plasma Thrusters
    - High power (≥ 10 kW)
    - High thrust-to-power ratio, long lifetime, large throttleability, thrust vectoring capabilities, high specific impulse, propellant friendly;
  - PEGASES thruster
  - NEPTUNE thruster
  - ECR thruster
  - Ponderomotive thruster
  - etc.
- Resistojets, arcjets, QCTs, etc.
- Novel thrust vectoring solutions
- European components in the areas of
  - valves,
  - tanks,
  - pressure regulators,
  - pressure transducers,
  - filters,
  - etc.
- Test facilities
  - for high power operation and related plasma diagnostics

- for operation with alternative propellants to xenon

- Modelling tools for thruster and cathode design and spacecraft thruster interaction
- New Solar arrays, direct drive, etc.

Cathode/ neutralisers (future technology improvements)

- high and very high current hollow cathode
- high current neutraliser
- long lifetime
- European components

  Cathodes are a very important equipment of an EP system and in some cases is the strating point of the thruster ignition. Many of these components are currently imported from outside Europe. And there is today no European product capable to deliver for high and very high current. For this reason alone an intensive development effort should be undertaken to develop European products.
- Operation with alternative / non-conventional propellants

Flow Control Units

- European non-dependence

  Flow control units are very important subsystems of most EP systems. The most common setup consists of stainless steel tubing with closing valve at the input, a proportional valve for gas flow control, flow restrictors, gas purifiers, and closing valves at the thruster and neutralizer exits. Many of these components are currently imported from the US and fall under ITAR restrictions. For this reason alone an intensive development effort should be undertaken to make FCU components and complete FCUs available from European sources.
- Increase mass flow ranges

  The expanded use of electric propulsion will require FCUs for a larger range of operational parameters. The most demanding application will occur in space science missions, e.g. for extremely accurate positioning of satellites. The e-LISA project has such a requirement and currently colloid thrusters are baseline, which avoids the need for a FCU and also reduces complexity considerably. However, other missions may prefer xenon thrusters and then the FCU becomes a critical technology.
- Miniaturisation

  Technologies developed in Europe include MEMS based as well as miniaturised FCUs. MEMS based FCUs can be very small and light, and may have the potential to control very low xenon flows with high precision. Applications are also foreseen in the LEO domain. Miniaturized FCUs operate with on-off valves and are much less bulky than the presently mostly used proportional valve designs. They can also work at high xenon pressure and may simplify pressure regulation of the electric propulsion system.

Power Processing Units (PPUs)

- Industrialisation

  Especially for an expected market in telecom and for navigation constellation a high degree of industrialisation is expected to improve the achieved competitive cost figures. Key factors of the industrialisation are:
    - Reduction of parts count for EEE components (ITAR?)
    - High degree of automated assembly
    - Simplification of the high voltage design to allow cost effective production
    - This could include for example:
    - Replacing potted high voltage designs by more optimized solutions
    - Optimization of high voltage transformers
    - Simple-to-manufacture high voltage transformers (i.e. planar transformers)
    - Reduction of functional blocks by shared functions
    - Smart redundancy concepts by switching matrix for low and high power supplies to thruster
    - Standardisation and optimised modular concepts

  New competitive solutions (control architecture simplification, optimization of Power Supply Control, multifunction power supplies, reducing the wiring, the mass and the size, cost optimization) could be based on new approaches oriented on an increase of cost reduction (e.g. extended COTS utilization, new modular simplified architectures)

- High Power
  - The perspective for telecom satellites and for navigation constellations has changed from “simple” station keeping to orbit raising. Therefore the required power level for thrusting has increased from an order around 1000-4000 W to 5000-20000 W (today’s future scenarios). Looking on the high end the limitation is given by the solar generator, which limits the available power for satellites to 20-25 kW for large satellites. For telecom satellites the power is typically used for operation of the payload at destination orbit, and the power for electrical station keeping is expected to be a small fraction of the overall power budget, while for orbit raising the full power is available as the payload is not active. Starting from the max. scenario the 20-25 kW power budget is aimed to be shared by 2-4 thrusters for redundancy reasons. So in near term PPUs for 5-10 kW are envisaged or are already under development (currently most of them targeting 5 kW). The bottleneck for high power is the supply of the main discharge (beam supply). The cell size of such a high power supply was 1.2-1.5 kW in the past, while now 2.5 kW per block are state-of-the art. For the future it could be interesting to further increase the power per cell to 5 kW.
  - In terms of high power needs this could be achieved by:
    - Operating a number of high voltage modules in parallel (for example 4*2.5 kW = 10 kW).
    - Increasing the power per cell (for example 2*5 kW = 10 kW)
  - In principle it is technically feasible to have many power cells in parallel: a number of up to 10 cells appears to be feasible, but has the disadvantage of higher costs due to part count.
  - Increasing the power per cell is challenging, as the technologies are pushed towards theirs limits. For example: the heat transfer within the module is limited. Suitable means could be:
    - Transforms with lower loss and better thermal coupling (planar transformers)
    - EEE components with lower losses (for example by use of wide band gap materials such as GaN or SiC)
    - High voltage insulation materials with better heat conductivity
    - Advanced combination of materials, e.g. use of copper and ceramic elements for increased heat transfer

- Low Power

  Although the main focus today appears to be on high power EP, there is still a minority of low power EP applications in the future especially for science missions and earth observation missions. Power range is 200 - 800 W and below, including micro-propulsion. Efficient PPUs are needed at low cost. In order to achieve this, modularity and configurability are an asset.

- Configurability

Trends derived from this are:

  - In-orbit reconfiguration:
    - Reconfigurable PPUs to serve North-South station keeping as well as orbit topping with the same PPU.
    - Change of voltage and current drive capability depending on the operation mode
    - Reconfiguration of clusters of thrusters for different operation scenarios
    - Hybrid Solution to drive different types of thrusters for different operational task (for example: mix of GIE and HET)
  - This kind of configurability requires switching/adjustment capabilities within PPU modules or in-between. There is an increased complexity, if high voltage lines are involved in this switching.
  - On-ground configuration:
    - On-ground configuration can be explored to ensure that a PPU can serve different thruster (for example HET from different manufacturers or of different power classes), and/or different redundancy and clustering scenarios. Re-configuration could be made by hardware (jumpers, adjustment of potentiometers, etc.), assembly variants or by programming (software parameter or EEPROM). In an ideal case, modules and PPUs could be produced and later tailored to a specific mission. The production of higher quantities of similar items could lead to significant recurring cost reduction (including less delta-qualification effort) and has a high potential to reduce lead times for PPU’s.

- Modularity

  Increased modularity seems to be an advantage to serve different missions and mission types. In an ideal case a PPU can be composed by a set of modules serving different types of high voltage power supplies, coil supplies (if any), valve control, flow control, heater control, neutraliser and keeper supplies, etc. A high degree of modularity could be in contradiction to reduce parts count of a PPU and has to be assessed for the targeted mission. For telecom and navigation missions the degree of modularity has to be further analysed to see how modularity can be implemented with a high degree of industrialization and related cost reduction. For scientific mission modularity could be a significant advantage to adapt easily and without new development/qualifications to a broad range of mission scenarios. A typical PPU modular architecture is composed by (Filter and Thruster Selection Unit Module, Filter Unit Module, Anode Module, Heater-Keeper-Ignitor Sequence Module).

- High(er) Voltage

  The current range for voltage is distributed between the HET in the 300-350 V range, the ion engines between 1000-2000 V and the FEEP in the range of 10-15 kV (at low power). In principle the HET PPU's tend to avoid high voltage potting and use standard PCB's in order to avoid the risk of internal breakdown (Paschen/Corona discharge), the 1000 V-2000 V is covered typically by potted designs, the 10-15 kV mandatory needs potted design. In principle the potted designs are easier to operate in "bad" vacuum pressure, but the production requires more effort and process knowledge and therefore is more costly. Regarding the size of potted high voltage module, the design driver is more the power per module and the space needed for handling/mounting during assembly and potting. Exceeding the range of 2000 V the high voltage required high voltage insulation distance will be significantly the driver for module size and mass is significantly the voltage as insulation distances typically increase in all three dimensions. Unknown fields to be further explored are:
    - Increase of operating voltage in non-potted designs
    - Increase of operating voltage in PCB's (single, double or multiple/-layer)
    - Use of potting materials with high heat transfer

- Direct Driving
  - Direct drive is an option for simplification of the overall spacecraft power system including the PPU: instead of taking the input power of a PPU from the regulated or unregulated power bus, the direct drive is drawing PPU power directly from the solar array. The basic motivation is an increase of efficiency and to avoid over design of the spacecraft power system only for EP needs. With this concept:
    - The PCDU power regulation and the battery of the spacecraft bus is not affected by the power sizing of the PPU
    - The main discharge current for the thruster is not regulated by the PPU
    - A simplification and cost saving for PCDU, PPU and battery is expected
  - However the electrical supply of the thruster can vary depending on the sun illumination, so an optimum working point and stability of thrust is not guaranteed.
  - New spacecraft power system design for such as the PCDU might be required to cope with higher voltage from solar panels or with specific solar array sections dedicated to EP.
  - The solar array need to be designed to supply high voltage
  - Thrusting is only in operation with sufficient sun illumination (not in eclipse)
  - Such a concept had been studied on ground by JPL with HET thruster and is proven in principle.
  - However there are technological limitations and risk:
    - High voltage solar arrays for space have never been flown up to now: therefore design, qualification and in-flight testing would require significant effort. Today's solar generators are built to supply 100 V buses, for direct drive with HET voltages of 300 V-600 V might be needed. Spacecraft charging effects can cause surprises and cannot be fully covered by simulation or on ground-testing. Therefore an in-orbit test bed might be needed. Much higher voltage for solar arrays (than 600 V) will significantly increase the technological complexity.
    - PCB's and EEE components for higher voltage are critical, especially semiconductors: todays radiation-hard MOSFET allow maximum 400 V in one device (including derating). This fact at least increases the complexity for circuitry handling the 300 V-400 V directly (switching or modulation).

- Power System Architecture
  - The power system architecture could be adapted to EP system by integrating PPU functions into the PCDU either in combination with direct drive or without direct drive. This type of integrated architecture may make sense for mission where the spacecraft architecture can be driven by the EP needs: exploration missions and launcher missions including space tugs etc.

- Components
  - The following component aspects are of high interest for PPU:
    - COTS
    - New Silicon Carbide Semiconductors (Rectifiers, Transistors)
    - New Gallium Nitride Semiconductors
    - Mixed analog/digital ASICs for efficient circuitry.

10 CONCLUSION

The studies and analysis of the requirements vs each application domain (Telecommunication, LEO, MEO, Space transportation, Exploration/interplanetary and science) in function of the already existing European EP systems were performed. It allow to identify the gaps that any EP system should cover for future markets and flight opportunities for each of those domains.

Medium and long term developments were identified and presented for already known European technologies with the objective of competitiveness of the Electric Propulsion European industry in the 2030 timeframe. Possible synergies between telecommunication, Navigation, Space transportation and Exploration missions could be identified.
New ways of thinking and new approaches shall also be encouraged to develop competitive EPS system for Telecom and LEO applications.

Finally, no restriction shall be made on any future development and innovative disruptive concepts that would allow Europe to be at the forefront in the EP area and be enabling future ambitious missions particularly in the arena of scientific, exploration or Space transportation opportunities. It is clear that these disruptive technologies shall at least be able to cover the same gaps as already existing and flying technologies and go one step further in performance if they wish to be competitive on future markets.