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Eine Innovationsanalyse für neuartige Technologien im Bereich erneuerbarer Energien

An innovation analysis for novel renewable energy technologies

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Abstract

Renewable energy technologies such as solar and wind are surface-area-limited (2D) in power density output. With the phasing out of fossil fuels, questions around renewables matching the pace of electric vehicle adoption highlight risks for blackouts in underdeveloped electric grids. New fundamental innovations in the energy space as well as perspective shifts by the wider government, business, and scientific communities may be required to address these concerns.

This study aims to explore a multitude of techno-economic perspectives surrounding a new class of renewable energy harvesting devices that overcome constraints of 2D, remarkably generating power in all three dimensions. Drawing from literary findings, industry and lead-user interviews, a customer needs-based concept design analysis (CODA) benchmarks these novel technologies against existing solutions in terms of customer satisfaction. Systematic economic and entrepreneurial drivers in the energy space inform baseline application selections for CODA and also help identify innovation strategies for future commercialization endeavors.

The benchmarking results unveil high-level distinguishing design characteristics in which novel energy technologies are better suited relative to existing technologies, highlighting encouraging possibilities for future applications. Novel energy research is still early, and the results involved numerous estimations on various technical aspects. Addressing risks in over or underestimating the technological potential requires further research, experimentation, and manufacturing advancements.

Through the systematic strategies identified in this paper, awareness and understanding of this field is increased. With this knowledge, actors and institutions can assuredly invest in legitimate research and ensure appropriate markets sectors and applications are targeted. Tactics that if realized, have wide societal impact and potential in disrupting the entire renewable energy technology space.

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List of Abbreviations

AHP	Analytic Hierarchical Process
ANP	Analytic Network Process
BWM	Binary Weight Matrix
CMOS	Complementary Metal-Oxide Semiconductor
CN	Customer Need
CODA	Concept Design Analysis
EC	Engineering Characteristic
ETIS	Energy Technology Innovation System
EV	Electric Vehicle
FCO	Ferroelectric Crystal Oscillator
FEE	Ferroelectric Electron Emission
GDP	Gross Domestic Product
HOQ	House of Quality
IBM	International Business Machine
IP	Intellectual Property
IPS	Inches Per Second
MDA	MacDonald Dettwiler and Associates
MEMS	Micro-Electromechanical System
MIT	Massachusetts Institute of Technology
MIM	Metal-Insulator-Metal
MTBF	Mean Time Before Failure
NET	Novel Energy Technology
ODM	Overall Design Merit
PE	Private Equity
PZT	Lead Zirconate Titanate
QFD	Quality Function Deployment
QFN	Quad Flat No-Leads

RF	Radio Frequency
SEM	Scanning Electron Microscope
SLGS	Single Layer Graphen Sheet
SOI	Silicon on Insulator
TRL	Technology Readiness Level
TSMC	Taiwan Semiconductor Manufacturing Company
TSV	Through Silicon Via
VC	Venture Capital
WSH	Wafer Stackable Height
ZOGP	Zero One Goal Programming
ZPE	Zero Point Energy

List of Symbols

α	Power variable for CODA
ρ	EC variable for CODA
η	Neutral or optimum point variable for CODA
τ	Tolerance variable for CODA
CS_i	Total customer satisfaction of CN i
N_i	Weight of CN i
MV_{ij}	Merit value of relationship ij
CF_{ij}	Correlation factor of relationship ij
SCF_i	Sum of correlation factors for CN i
ρ	Planck's second theory vacuum energy term
c	Speed of Light
f	frequency
h	Planck's Constant
k_B	Boltzmann's Constant
T	Absolute Temperature
η	Noisy stochastic term related to fluctuation dissipation theorem
v	Velocity of a particle
ξ_v	Fluctuating Force
m	Variable describing Brownian motion
θ_J	Thermal Resistance
T_A	Ambient Temperature
T_J	Junction Temperature
µm	micrometer
nm	nanometer

1 Introduction

1.1 Background and Scope of Research

In 2022, global energy demand continues to rise. With the push towards more renewables, western countries are weaning themselves off oil and looking towards alternative energy sources. Driving this shift are incentives for electrification encouraging widespread electric vehicle (EV) adoption. But concerns regarding grid stability (Muratori 2018; Long and Jia 2021) are placing policymakers in difficult situations "[T]he currently proposed expansion of the German electricity grid will not be sufficient to cope with increased electricity demand from uncoordinated EV charging" (Staudt et al. 2018, p. 1435). Officials in California (one of the most popular EV States) are already projecting summer-2022 blackouts and asking residents to limit consumption during peak times (Ingrassia 2022; Mulkern 2022). If the growing demand for energy is outpacing renewable energy growth, new <u>fundamental</u> innovations in the energy space may be required to address these concerns.

Current renewable energy sources (solar, wind) are 2-dimensional, relying on surface area to generate power. If though, through new perspectives on energy, scaling into the 3rd dimension was possible, power density could be massively improved. This could revolutionize all forms of technological systems and upend long held foundations in scientific communities. In this paper, I explore a new class of novel renewable energy technologies, that if developed fully, have the potential to disrupt the entire renewable technologies industry. I develop arguments through aspects of philosophy, technology, economy, and customer needs, to create a wholistic understanding of the strategies required to make innovation in this novel energy space successful.

From a management perspective, this topic has not been well researched, likely due to unawareness, complexities, or uncertainties surrounding the field. This research attempts to demystify and bring awareness to the remarkable energy research taking place today.

1.2 Normal vs Extraordinary Science: The Kuhnian Perspective

The discovery of the photovoltaic effect in 1839 exemplifies a departure from *normal science*. Most contemporary Victorian-era scientists held the paradigmatic view that light was simply a wave. This apperception led to a developing ignorance that one could produce electrical energy from the sun, a skepticism later rectified by Albert Einstein in the early 20th Century (Robertson 2016, p. 10).

1.2.1 Normal Science

Thomas Kuhn, well-known for his study on the philosophy of scientific development, first defines normal science in his influential essay: *The Structure of Scientific Revolutions* (1962). " 'normal science' means research firmly based upon one or more past scientific achievements, achievements that some particular scientific community acknowledges for a time as supplying the foundation for its further practice" (Kuhn 1970, p. 22). In this view, normal science is cumulative and generates a stockpile of knowledge over time. Kuhn metaphorically contrasts normal science to jigsaw puzzle solving in which a set of limiting-rules are employed such that "all the pieces must be used, their plain sides must be turned down, and they must be interlocked without forcing until no holes remain" (1970, p. 50). By broadening the use of the term 'rule' to mean 'established viewpoint or 'preconception', Kuhn relates puzzle solving characteristics to a set of principals observed in normal science; a network of strong scientific consensuses encompassing theories, methodologies, instrumentation, assumptions, and facts constitute these principals as 'rules' (1970, pp. 51–54).

1.2.2 Paradigms and Anomalies

At a broader level, deriving the rules of normal science requires an abstract prerequisite concept or 'paradigm' according to Kuhn. "Rules, I suggest, derive from paradigms, but paradigms can guide research even in the absence of rules" (1970, p. 54). A Paradigm, he defines, manifests at the beginning of a universally recognized scientific achievement and shares two essential characteristics:

1. The achievement is sufficiently unprecedented to attract an enduring group of adherents away from competing modes of scientific activity. (1970, p. 22)
2. The achievement is sufficiently open-ended to leave all sorts of 'puzzles' for the redefined group of practitioners to resolve. (1970, p. 22)

From Kuhns view (1970, p. 121), a paradigm's role serves as a vehicle for scientific theory, delivering information to scientists about the entities and behavior of the natural world, "a map whose details are elucidated by mature scientific research. […] Through the theories they embody, paradigms prove to be constitutive of the research activity" (1970, p. 121). The paradigm, Kuhn elaborates, is trusted by the scientific community and the principals it defines are taken for granted. This enables scientists to freely engage their normal scientific activities with little thought given to the credibility of the paradigm in which they practice (Gijsbers 2022).

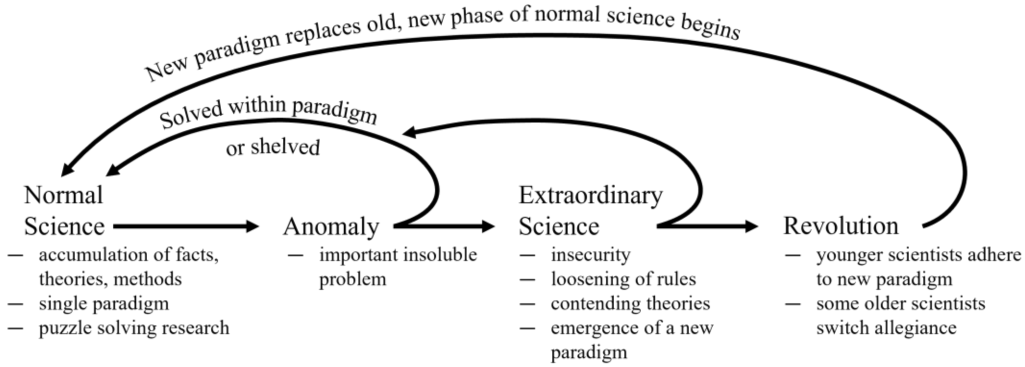
Demonstrated by historical periods of the past[1], normal science plays out as various puzzling games. But what happens when a piece of the puzzle does not fit, an anomaly? According to Kuhn (1970, p. 93), anomalies don't necessarily constitute a crisis, but he states "When, […] an anomaly comes to seem more than just another puzzle of normal science, the transition to crisis and to *extraordinary science* has begun. The anomaly itself now comes to be more generally recognized as such by the profession. More and more attention is devoted to it by more and more of the field's most eminent men" (1970, p. 94). Whether the anomaly calls out fundamental generalizations of the current paradigm, or creates an inhibition to existing practical application, perceptive researchers will feel compelled to investigate in new and nontraditional ways.

1.2.3 Extraordinary Science

"All crises begin with the blurring of a paradigm and the consequent loosening of the rules for normal research" (1970, p. 96). Some researchers begin abandoning standard practice and extraordinary research ensues, exploring new and unique experiments with creativity and randomness, the deconstruction of stereotypes, and the spawning of speculative theories (1970, pp. 99, 101). Kuhn writes: "The proliferation of competing articulations, the willingness to try anything, the expression of explicit discontent, the recourse to philosophy and to debate over fundamentals, all these are symptoms of a transition from normal to extraordinary research" (1970, p. 103). This transition, Kuhn argues (1970, p. 178), is not just another mechanism to scientific progression, but paves the way for scientific revolutions. Extraordinary science, if successful in its endeavors, may lead to complete change in perspective, or in Kuhn's words, a *paradigm shift*. (Waller 2020). Described through the historical examples Kuhn introduces, the transitions from normal to extraordinary research provide compelling evidence of Kuhn's paradigmatic cycle as illustrated in figure 1.

[1] " 'Ptolemaic astronomy' (or 'Copernican'), 'Aristotelian dynamics' (or 'Newtonian'), 'corpuscular optics' (or 'wave optics'), and so on " Kuhn 1970, p. 22.

Figure 1: The revolutionary character of paradigm shifts and the cyclical nature of science (a schematization of Kuhn, 1970)



Source: Own representation (based on Leahey (2004, p. 14))

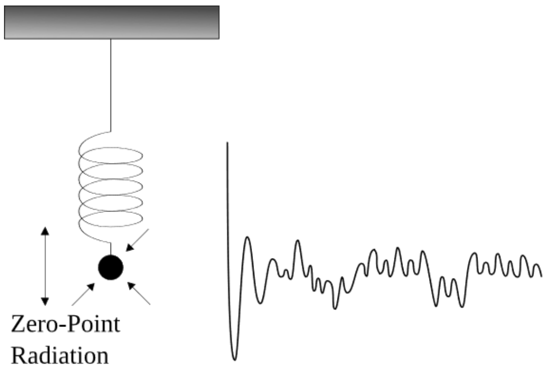
1.3 Extraordinary Energy Science

Nikola Tesla in his 1891 address to the institute of electrical engineers in New York foreshadowed a bold claim for the future of energy science: "Throughout space there is energy. Is this energy static or kinetic? If static our hopes are in vain; if kinetic—and this we know it is, for certain—then it is a mere question of time when men will succeed in attaching their machinery to the very wheelwork of nature. Many generations may pass, but in time our machinery will be driven by a power obtainable at any point of the universe" (Tesla 1904, as cited by Valone 2009). Further developments in the early 20th century led by Planck, Einstein, Stern, Nernst, and Heisenberg, indirectly theorized Tesla's remarks on vacuum energy during the pioneering stages of quantum mechanics. In a 1915 letter to a colleague, Planck wrote: "I have almost completed an improved formulation of the quantum hypothesis applied to thermal radiation. I am more convinced than ever that zero-point energy is an indispensable element. Indeed, I believe I have the strongest evidence for it" (van Delft 2007, as cited by Kragh 2012, p. 12). But between 1915 and the early 1920s, enthusiasm for zero-point energy (ZPE) subsided. It was not until 1924 that new experiments in molecular spectroscopy showed that ZPE was not a property of material systems, but rather of empty space in electromagnetic fields with an energy of ½ quanta (Kragh 2012, 15, 22) as shown in equation (1); and by 1926 " it became customary to see the zero-point energy as a straightforward consequence of Heisenberg's uncertainty principle for position and momentum" (2012, p. 23). Later research by Nernst identified cosmological relevance for ZPE. Since then, many physicists have adopted ZPE density and the cosmological constant to be one in the same, preluding ZPE to the 'dark energy' or 'dark matter' terms we hear today (Peebles and Ratra 2003, as cited by Kragh 2012, p. 2).

$$\textit{Planck's second theory} \quad \rho(hf) = \frac{8\pi f^2}{c^3}\Bigg(\underbrace{\frac{hf}{\exp{(hf/k_B T)} - 1}}_{\text{thermal energy}} + \underbrace{\frac{hf}{2}}_{\text{zero-point energy}}\Bigg) \tag{1}$$

Energy density in space = thermal energy zero-point energy

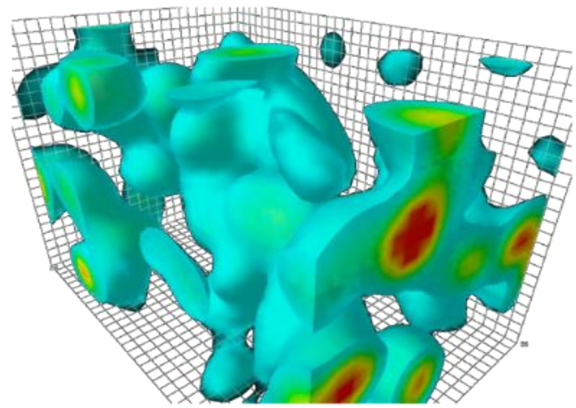
Figure 2: Mechanical analogy for ZPE oscillations



ZPE can be likened to a hanging mass on the end of a spring. Although only shown here as a single mode of oscillation, ZPE is the accumulation of all frequencies and directions of vibration. Unlike a mechanical system, a ZPE oscillation will maintain a minimum energy state (Puthoff 1994).

Source: Sparkyscience (2022)

Figure 3: Visualization of ZPE oscillations in 3D space



ZPE pervades all space and is the random electromagnetic field oscillations that exist in a vacuum and at 0 degrees Kelvin. These transient fluctuations produce virtual photon pairs governed by the Heisenberg uncertainty principal.

Source: Leinweber (2015)

1.3.1 Potential of Zero Point Energy

From a technological perspective, ZPE has significant implications. Developing devices that can capture quantum fluctuations at high power densities would unlock power-on-demand applications, essentially hybridizing or replacing all fuel and battery systems. Researchers investigating have hypothesized energy densities on the order of 10^{108} Joules / cm^3 (Valone 2009, p. 18). While there is still some debate on this figure as it's dependent on an unknown cutoff frequency from equation (1), even at conservative estimates, gram for gram ZPE is 10's of orders of magnitude more power dense than nuclear reactors. A conclusion that intrigues perspective shift, in that "space itself contains more energy than matter does for any given volume" (2009, p. 18). Established paradigms in the scientific communities have mostly ignored ZPEs potential as it brings into question the 2nd law of thermodynamics. However, in a presentation titled: *Beyond the Thermodynamic Limit: Template for the Second Law Exceptions* (2022), Professor Daniel Sheehan at the University of San Diego department of physics states multiple exceptions highlighting the nuanced definitions of boundaries in thermodynamic systems. “To put this into perspective, the second law has been undergoing really unprecedented scrutiny over the last 25 years, roughly […] four dozen second law challenges have reached into the scientific literature since the mid-1990s” (2022, t=8:22). Outside of the thermodynamics debate, other investigations by Professor Claus Turtur in Germany have classified potential ZPE devices summarized in table 1.

Table 1: Overview of ZPE-converter concepts

System	Power segment	Examples of Application	Chances of technical success	Energy price
Infinite battery	1 … 50 Watts	Cell phones, Laptops, in the worst case only a revolution of the world battery market	90 % ± 10 %	0,5 . . . . 5 cent / kWh
Motionless-Converter	20 Watts … 5 kW	E-Bikes, transportable devices, small electric cars	75 % ± 25 %	0,2 . . . . 1 cent / kWh
Hydrogen-systems	100 Watts … 300 kW	Transportation sector (cars, ships, airplanes, motorcycles, etc…), motors	80 % ± 20 %	0,05 . . . . 0,5 cent / kWh
Magnetic motor	5 kW … 100 MW	Households, energy supply for industry, only stationary consumers	90 % ± 10 %	0,02 . . . . 0,1 cent / kWh
Magnetic switch	100 W … 5 kW	Transportable devices, Households (low speed motors, electronic systems)	65 % ± 35 %	0,01 . . . . 0,5 cent / kWh
Gravity- and hydraulic systems	10 W … 20 MW	Craftsmen, catering service, etc… (stationary application, medium sized business, Handicraft enterprises)	60 % ± 40 %	0,05 . . . . 1 cent / kWh
Capillary pumps	100 W … 100 kW	Handicraft enterprises, poor countries (stationary application)	60 % ± 40 %	0,1 . . . . 0,5 cent / kWh
Electron beam converters	1 Watts … 1 kW	Arbitrary electrical devices of all kind	50 % ± 50 %	0,1 . . . . 0,5 cent / kWh

Source: (Turtur 2021, p. 3)

Through extraordinary research of such ZPE concepts and potential widespread adoption in the future, large scale power plants could be phased out as more and more of the world’s devices start generating local power. A revolution in global energy supply and demand.

1.4 Economics of Energy Innovation

With the promise of extraordinary research ultimately leading to technological breakthroughs for society, it is important to understand how these advancements will best proliferate from an economic perspective. The Energy Technology Innovation System (ETIS) as defined by Gallagher et al. (2012) “is a systematic perspective on innovation comprising all aspects of energy transformations (supply and demand); all stages of the technology development cycle; and all the major innovation processes, feedbacks, actors, institutions, and networks.” Here, the economics of energy innovation are explored in detail, providing strategy for researchers and entrepreneurs looking to have impact in energy markets. In this paper, I reference ETIS to make a selection of market sectors and technology applications that, in my opinion, provide the best chance for success (compatible) in adopting novel energy technologies. Given the many barriers to research and development (R&D) and commercialization such as the 'Valley of Death'[2] or lack of economies of scale, it is important to choose applications and markets that mitigate these risks. In Section 2.2, I will highlight key features and drivers of ETIS that relate to the chosen market and application selections as well as articulate the details of these selections in Section 3.2, which will be evaluated by a qualitative model later in this paper. In doing so, the market sectors and the applications selected will address the first part of this paper's research question:

> **Given a selection of market sectors and applications**, to what extent do novel energy technologies satisfy customer needs when contrasted to existing technologies?

The second part encompasses the qualitative portion of this paper and will be introduced further in the next section.

1.5 Customer Needs and Research Question

In the technological marketplace today, innovation that matches customer needs often distinguishes the successful from unsuccessful products. This contrasts with the old technological economy (1970-1990) in which higher levels of quality or differentiation in technology were the single sources of competitive advantage (Lee-Mortimer 1995, p. 38). Innovation through customer needs mapping unlocks new efficiencies for a firm to explore. "When organizations direct their efforts towards meeting their customer requirements, internal conflicts are minimized, development cycle times are shortened, and market penetration is increased with improved product quality, gaining better customer satisfaction and higher revenues" (Kwong et al. 2007, p. 668). The obvious point here is that successful firms innovate, and successful innovations are governed by how well they match customer needs. If qualitative predictions can be made as to how well a technology will fair in the marketplace based on regression to customer needs, then to answer the research question:

> **To what extent do novel energy technologies satisfy customer needs when contrasted to existing technologies?**

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[2] The 'Valley of Death' or 'funding gap' exists between early research and commercialization of a new product. Often this gap is driven by initial government expenditures for basic research and subsequently fades at later stages in the innovation process due to insufficient attention. See: Ford et al. 2007 *A Valley of Death in the Innovation Sequence: An Economic Investigation*

is similar to answering this other question: how successful will novel energy technologies be relative to existing technologies? Therefore, in this paper, I will use a qualitative and conceptual scoring methodology, introduced in Section 2.3, to answer these questions and in doing so, shed light on the relative merits of existing and extraordinary Novel Energy Technologies (hereafter referred to as NETs).

2 Literature Review

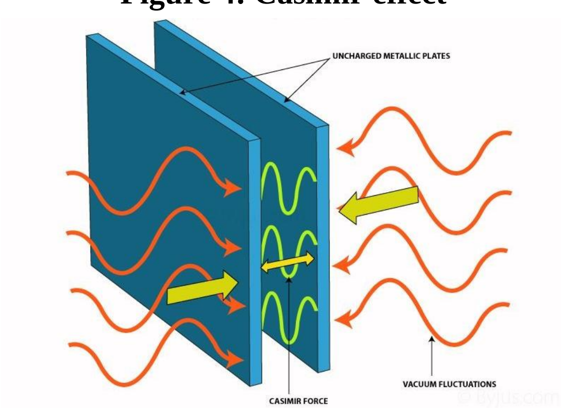
2.1 Zero Point Energy Research

The physics of ZPE has captivated niche groups of researchers over the last half century. Growing interest in the field has seen exponential numbers of publications highlighting potential ZPE effects. Discussed next is a condensed timeline evidencing the major scientific developments towards the extraordinary research happening today.

2.1.1 Past and Present

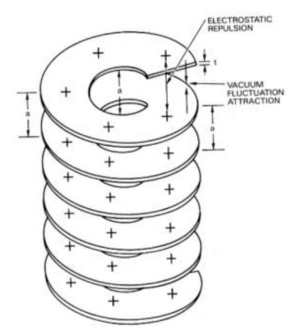
In 1948 Henrich Casimir hypothesized a force directly responsible by ZPE. The force he claimed, would cause two perfectly conducting uncharged plates to start attracting at distances < 1µm. 50 years later this Casimir force would be experimentally confirmed (Lamoreaux 1997), bringing clarity to 'stiction' effects[3] seen in the nanotechnology industry (Valone 2009, p. 38). By the 1980s, a new energy research paradigm spearheaded by Dr. Robert Forward's thought experiment (1984) would captivate groups of researchers. Dr. Forward suggested ZPE could be harvested through a Casimir like battery (figure 5).

Figure 4: Casimir effect



Source: E Journal (2022)

Figure 5: Dr. Forwards Casimir battery thought experiment



Source: Forward (1984)

[3] During the production of micromechanical systems (MEMS), stiction due Casimir forces causes tools and other material bodies to bond, complicating the fabrication processes. See: Serry et al. 1998 *The role of the casimir effect in the static deflection and stiction of membrane strips in microelectromechanical systems*

Supported by the Lamb Shift discovery[4], further work by Puthoff (1987) theorized that ZPE sustains the electron ground-state orbit in a hydrogen atom through the counteraction of the Coulomb potential with spontaneous creation and annihilation of virtual particles (Valone 2009, p. 39). This idea initiated investigations into whether a Casimir cavity could be used to disrupt the Coulomb balance, allowing electrons in hydrogen gas to spin-down to lower orbits releasing photons (Dmitriyeva and Moddel 2012). The experimental results were in-conclusive but continued research in ZPE extraction have led to potential breakthroughs.

In 2021, a team from the University of Colorado published new findings for their metal-insulator-metal (MIM) tunneling devices. By applying an optical Casimir cavity on one side of the device, suppression of zero-point fluctuations in that region upsets the electron tunneling balance in the MIM sandwich resulting in a net electron flow or current (Moddel et al. 2021). The implications are phenomenal, extrapolating the device scale to $1m^2$, the projected power density produced could be $70W/m^2$ (Moddel 2022), 13x more than conventional photovoltaic cells (Miller and Keith 2018).

Figure 6: MIM open cavity tunneling device stack-up

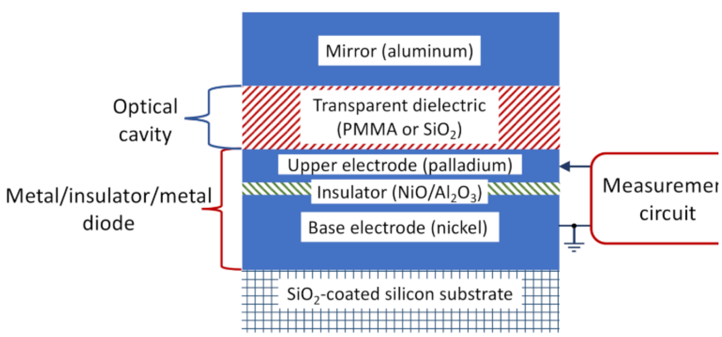
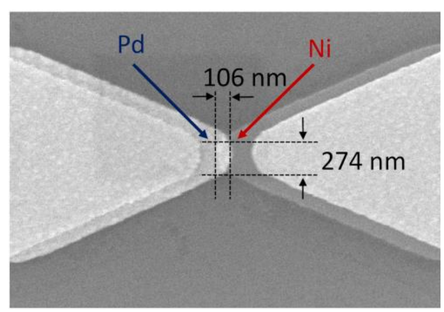


Figure 7: Scanning Electron Microscope (SEM) image of MIM device



Source: Moddel et al. (2021)

Independent of Moddel's work, researchers at the University of Arkansas have been investigating charging of capacitors through graphene fluctuations (Thibado et al. 2020). The researchers hypothesize the graphene fluctuations are due to thermal forces (Brownian motion) in the environment as indicated by the Ito-Langevin equation (2).

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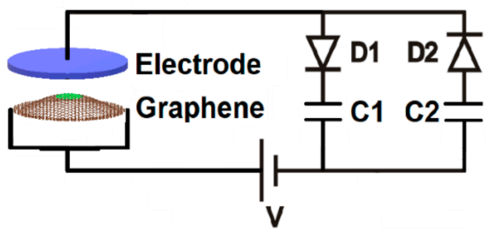
[4] The lamb shift, discovered in 1947, is a small difference in electron orbital energy levels between $2S_{1/2}$ and $2P_{1/2}$ of a hydrogen atom caused by vacuum fluctuations in and around the atomic structure. See: Pipkin and Lindsay 2002 *Encyclopedia of physical science and technology: Atomic Physics*

$$m\frac{dv}{dt} = -\eta\, v(t) + \sqrt{2k_B T\eta}\, \xi_v(t) \quad (2)$$

drag force thermal force

However, during a recent presentation, the lead author admitted that ZPE had not been considered as a source of motion and warranted further investigation (Thibado 2022, t=55:21). Numerous literatures cite electromagnetic fields as imparting Lorenz forces onto single layer graphene sheets (SLGS) and could support a ZPE claim (Murmu et al. 2013; Muschik et al. 2014; Guo et al. 2018). Whatever the source may be, the experimental devices (figure 9) have demonstrated excellent energy harvesting capabilities at $1W/m^2$, on par with wind energy (Miller and Keith 2019).

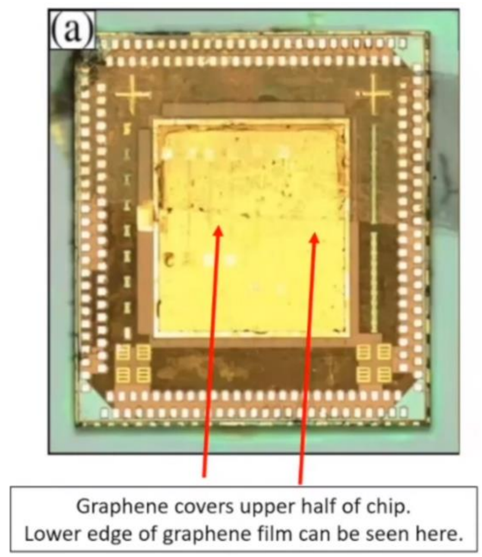
Figure 8: Graphene energy harvesting circuit



As the graphene capacitor fluctuates, charge flows through diodes D1 & D2 and charges capacitors C1 & C2 respectively. The circuit, when operated at its maximum output power, was found to have an efficiency of 50%.

Source: Mangum et al. (2021)

Figure 9: 5x5mm TSMC chip containing harvesting circuit

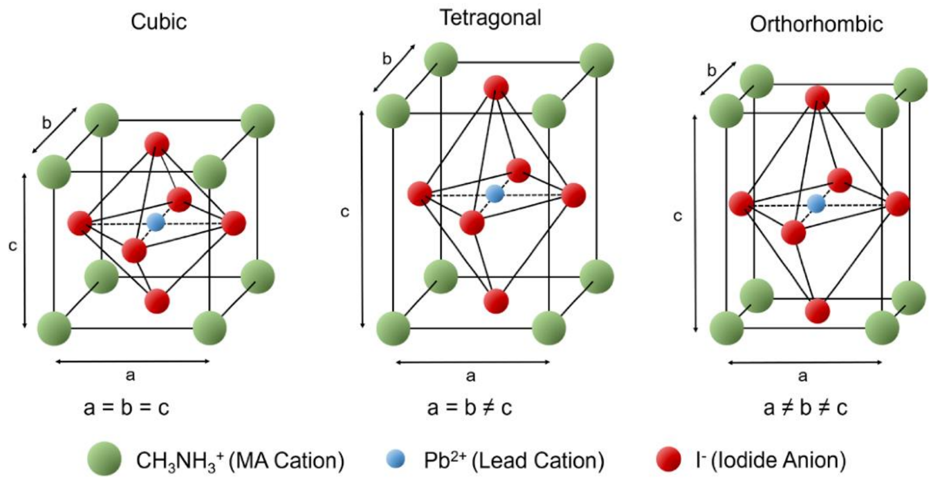


Source: Thibado (2022)

Other research by a Munich laboratory has been investigating ferro-electric electron emission (FEE) through novel material science. The effect is seen during a polarization reversal of a perovskite molecule (figure 10) in which a phase change from polarized (Tetragonal), to re-verse polarized (Orthorhombic) is invoked (Rosenman et al. 2000). Inspired by FEE, the researchers have discovered that by mixing several different perovskite materials (with different phases) into a single multi-phase ceramic[5], a property within ferro-elastic domain

[5] By integrating a quantum paraelectric perovskite into ferroelectric PZT (lead zirconate titanate) a multi-phase quantum ferroelectric ceramic material is created. (M. Reid, personal communication, 6/24/2022)

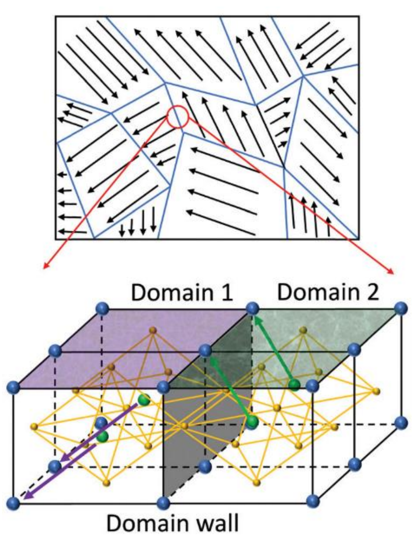
Figure 10: Phases of a perovskite molecule



Source: Thomson (2018)

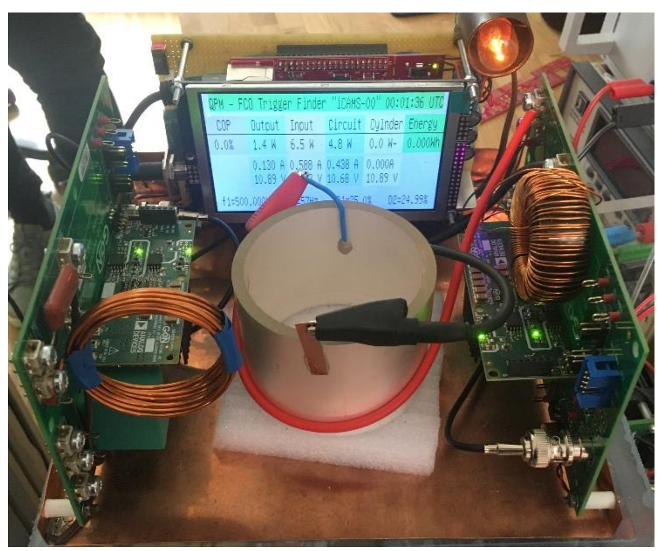
walls can be exploited. When tuned to phase-criticality, the material is able to channel ZPE quantum fluctuations into the observable domain. Due to an anisotropic property, polarization reversal in a vibrating domain wall (figure 11) generates more phonons (acoustic waves) in one direction than in the other. At the electrodes the acoustic waves are converted into a piezoelectric current (M. Reid, personal communication, 6/24/2022). If successful, the results will be remarkable. Research is still early but based on preliminary experimental results and literary findings surrounding FEE, the researchers are expecting power densities on the order of 1kW/kg (M. Reid, personal communication, 5/12/2022).

Figure 11: Perovskite domain walls



Source: Sun et al. (2021)

Figure 12: Ferroelectric Crystal Oscillator (FCO) cell test setup



Source: Quantum Power Munich GmbH (2022)

2.2 The Energy Technology Innovation System

The economic levers that can enable sustained innovation for NETs can be described through three core ETIS drivers: knowledge and learning, economies of scale and scope, and the roles of actors and institutions. The details discussed in these sections justify the market sector and application selections later in Section 3.2.

2.2.1 Knowledge and Learning

Following from the guidelines of ETIS, knowledge and learning reveal critical aspects for successful energy innovation. Knowledge can generally be split into three categories: knowledge production, spillovers, and depreciation. The accumulation of new knowledge is apparent during R&D and is a powerful driver of innovation. Often though, underinvestment in knowledge capture in the form of intellectual property (IP) rights results from the *non-appropriability of knowledge*[6]. As knowledge is largely a public good, without IP rights, there are challenges in controlling or restricting use (Gallagher et al. 2012, p. 141). Consequently, this leads to less attractive incentives for investors in the private sector and may suppress commercialization of novel energy products.

With knowledge generation, naturally the ability for spillovers can occur. According to ETIS this is a desirous effect as it promotes impact growth and productivity in localized geographic regions (Jaffe and Trajtenberg 1998, as cited by Gallagher et al. 2012, p. 141). This makes sense as not only do patterns of patents citations imply localized spillover as described by Jaffe and Trajtenberg, but technology spillover is typically more prevalent when a firm is surrounded by a high concentration of suppliers and competitors focused on that industry (Koo 2007). Easy transmission of technological knowhow also stimulates public and private R&D, creating incentives for niche market deployment. Programs that encourage entrepreneurs lead to further market growth and price reductions for the new innovative energy technology and augment that market sector's ability to generate new knowledge (Gallagher et al. 2012, pp. 141–142).

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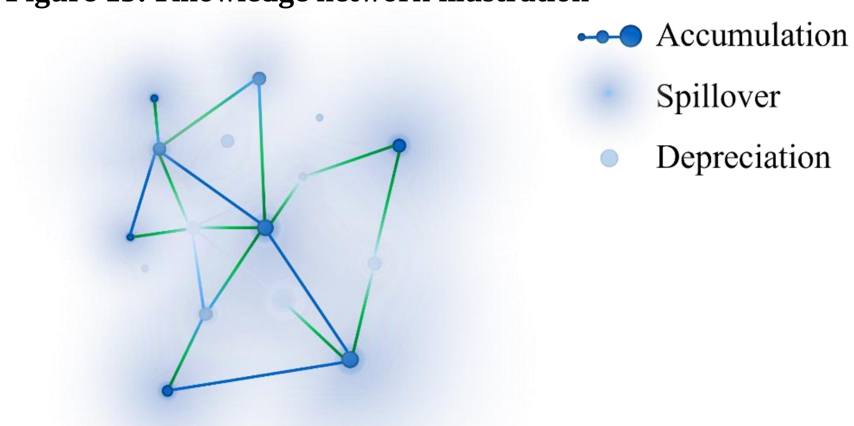
[6] Non-appropriability of knowledge can be understood through Schumpeterian profits; namely "the profits that exceed the risk-adjusted return to innovative investments" (Nordhaus 2004, p. 4) covers value metrics such as social value, intellectual property rights, and market power. See: Nordhaus 2004 *Schumpeterian Profits in the American Economy*

Certainly, concentrated knowledge growth has widespread benefits; however, the issue of knowledge depreciation should also be recognized. Two challenges occur in this respect: high turnover frequency in firms or institutions and insufficient knowledge ‘recharge’. When expert scientists, engineers, or managers, “holders of [tacit] knowledge” (Gallagher et al. 2012, p. 142) leave their place of work or shift their focus to different projects, stocks of knowledge are lost without comprehensive knowledge documentation (Boone et al. 2008, as cited by Grübler and Wilson 2013, p. 138). Therefore, when the minimizing of turnover is insufficient, internal firm policies that enforce documentation and knowledge retention practices can be employed to counteract. In addition, knowledge depreciation also propagates through technological obsolescence resulting from lack of ‘recharge’ (Evenson 2002, as cited by Grübler and Wilson 2013, p. 136). Grübler and Wilson write: “in cases where innovation proceeds rapidly such that old technological knowledge is no longer relevant for updated processes/techniques but new learning cannot proceed quickly enough[.] […] Both dimensions of knowledge depreciation are of particular concern in energy technology innovation systems when rapid rates of innovations coincide with erratic funding and policy support” (2013, p. 136). Following from this rationale, it is clear that increasing orientation of funding and policy towards connecting universities and institutions to innovative energy sectors is probably a good idea. Closing the knowledge recharge gap may eliminate the large depreciation rates (10% to 40% per year) as seen in the available literature (Gallagher et al. 2012, p. 142) and will likely promote steady energy innovation success over long time horizons.

Figure 13: Knowledge network illustration



The graph network depicts how knowledge could distribute over time in a localized region. Larger and contrasting nodes represent new and increasing knowledge accumulation whereas faded and disconnecting nodes portray firms experiencing technical obsolescence or turnover (knowledge depreciation). The blurred gradients imply spillover with larger amounts occurring closest to gradient centroid.

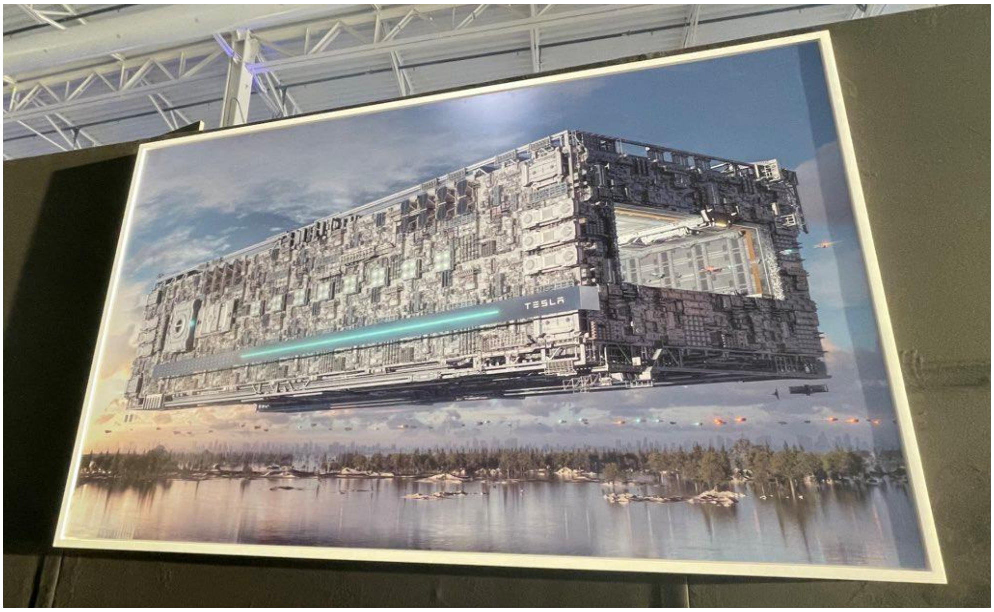
Source: Own representation

The influence of knowledge and learning policies in commercializing breakthroughs from extraordinary energy research shouldn't be underestimated. From the ETIS perspective, financial strategies that prioritize IP rights by allocating appropriate funds will attract external investments; encouraging spillovers through open sharing/licensing of technological knowhow as well as strategic geographic placement for R&D operations will generate new knowledge and reduce costs over time; and setting good documentation policies as well as developing strategic partnerships with universities and other firms will tend to minimize turnover risks and increase recharge rate. All the forementioned steps should maximize success in a researcher's/firm's innovative endeavors.

2.2.2 Economies of Scale and Scope

It is well understood the benefits of spreading fixed costs over more units, but with new technologies the feasibility of this is attenuated. Elon Musk has continually stated that relative to building a prototype, reaching mass production is extremely difficult: "The extreme difficulty of scaling production of new technology is not well understood. It's 1000% to 10,000% harder than making a few prototypes. The machine that makes the machine is vastly harder than the machine itself" (Musk 2020).

Figure 14: Artist's rendition of the machine that builds the machine



Source: Winkelmann (Artist), photo by Johnna Crider (2022)

How then should new energy technologies navigate prohibitive mass deployment? From the literature, economists have emphasized that specialization and standardization can be important milestones in reaching large scale manufacturing. Although in the economic sense the term ‘specialization’ tends to refer to division of labor often referencing assembly line production (Edwards and Starr 1987, p. 192); here, I explore the term to not only mean the efficiencies obtained through repetitive practice and learning in production, but also specialization in the sense of niche products. ETIS authors briefly mention this point: “Economies of scale describe reductions in unit costs as unit size […] expands. Larger devices […] allow fixed costs to be spread over larger units” (Gallagher et al. 2012, p. 142). Augmenting this thought further, I would argue that unit scale is not the only factor. Product complexity with highly specific customer needs should also fall under the umbrella of specialization as a means to achieve scale. By amortizing costs of new technologies into larger or highly specific lower quantity products, niche markets can help reduce new technology adoption risk. A recent techno-economic study by researchers at Massachusetts Institute of Technology (MIT) emphasized the importance of high-value niche markets for bringing cutting-edge photovoltaic technologies to commercial maturity (Mathews et al. 2019); highlighting that “customers in such markets are more comfortable paying a higher price for more sophisticated products” (Bellini 2020). Furthermore, markets and firms that are accustomed to niche product business models already possess the R&D drivers required for new technology integration. “Niche market customers can provide feedback on operational issues to researchers and entrepreneurial producers, namely through learning by-using, usually pushing to improve technology features, and to implement innovation in the production process which will reduce the business-risk for future diffusion” (Rai et al. 2010, as cited by Elia et al. 2021, p. 4). In this way, maturation of new technology in specialized applications through real-world deployment and manufacturing processes, complementary with the previously stated knowledge categories, often unlocks new opportunities for mass manufacturing over time.

Alongside specialization, standardization of NET can also stimulate efficient manufacturing, gradually building scale and demand growth. (Gallagher et al. 2012, p. 142). Standardization in this perspective covers a broad range of topics including processes for the production of knowledge (see 2.2.1), modular design practices, and vertical integration strategies (Grübler et al. 1999; Grübler et al. 2012; Armour and Teece 1980).

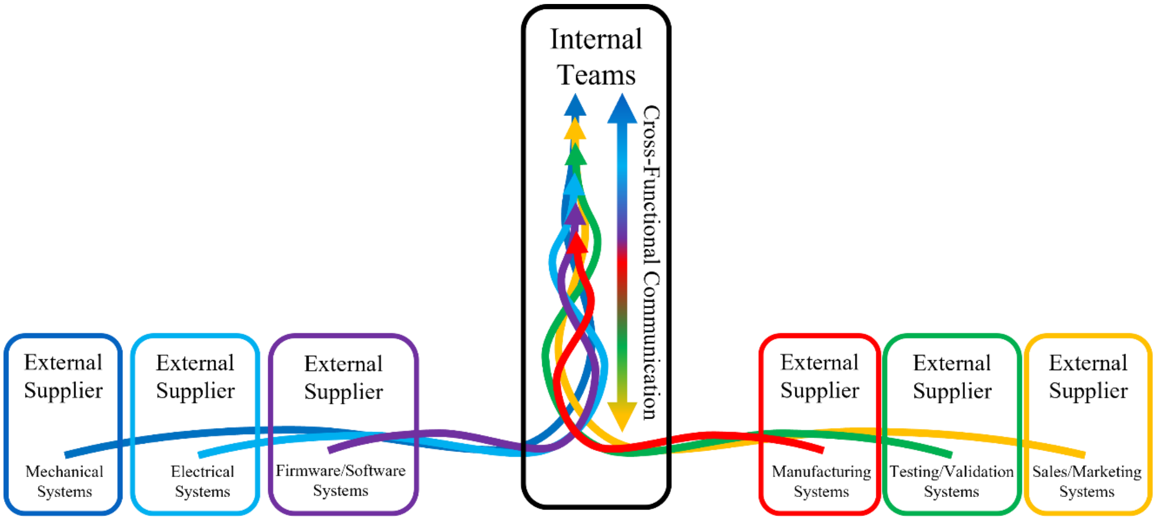
Modularity of new technologies, for example, increases use-cases and enhances ease-of-integration into larger or more complex products. In her well cited paper on modular systems theory, Schilling writes: “Modularity exponentially increases the number of possible configurations achievable from a given set of inputs, greatly increasing the flexibility of a system. […] The more heterogeneous [(complex)] the inputs are that may be used to compose a system, the more possible configurations there are attainable through the recombinability enabled by modularity" (2000, 312–317). The desire for modularity can also drive standardization across product lines. This requires enforcing interoperability during design which then allows basic changes to size or form-factor. "Interoperability can be defined as the ability of modules to inter-connect in a way that enhances performance in a predictable manner. By creating interoperability between different modules, new functions and services are made possible. Compatibility standards guarantee a level of interoperability between modules" (van Wegberg 2004, p. 461). For instance, aircraft manufacturers like Boeing and Airbus manufacture airframes to fit a variety of standardized engine sizes while maintaining common interfaces. Engine manufactures therefore reap modularity and standardization benefits through their catalogue offerings (Schilling 2000, p. 319). Overall, these modular design practices open up economies of scope which "describe the reduction in unit costs that can be achieved by producing more products jointly as opposed to individually" (Grübler et al. 2012, p. 1687). In addition, cost savings are amplified when modular design practices transfer to the factory environment, enabling "machinery and production processes [..] [that] facilitate and speed-up the process of change-over between products" (Grübler et al. 2012, p. 1687).

Standardization can be further complemented through vertical integration strategies. Strategies that "can facilitate the implementation of new processes or the introduction of new products when complex interstage interdependencies are involved (Armour and Teece 1980, 471). Two rationale for how vertical integration strategies supports eventual product standardization are exemplified through speed and parallelization of tasks. Internal horizontal communication lines across teams and departments precondition the approach. "For example, Zirger and Hartley found that fast developers in electronics had "teams that were cross functional, dedicated, included fast time to market as a development goal, and overlapped development activities"" (Zirger and Hartley 1996, as cited by Liker et al. 1999). This internal cross-functional integration bridges information gaps that otherwise exist in more hierarchical structures, enabling fast knowledge transfer between teams and incentivizing thorough collaboration on design standards (Liker et al. 1999, p. 249). This is especially important during the early design stages of novel technologies; developing consensus and commonizing design goals between mechanical, electrical, firmware, validation, sales, and manufacturing teams is the imperative. "[I]f the introduction of technology at one stage involves adaptation or adjustment in a preceding or a subsequent stage, then common ownership of the various stages of production will enable the necessary adaptations and adjustments to be made in a timely and efficient fashion" (Armour and Teece 1980, p. 471). For tasks that cannot be accomplished internally, then this is also true for relations external to a vertically integrated firm. Therefore, it is critical that during supplier negotiations, the focal firm mitigate unwanted behavioral uncertainty[7]. Requesting access to design files, source code, and setting requirements for design standards and the suppliers manufacturing processes for example, can mitigate this risk (Veer et al. 2016, p. 5). Without such contingency plans, the focal firm risks jointly incompatible decisions in various design stages (Armour and Teece 1980, p. 471), thereby slowing down progress and parallelization efforts. Contrarily, when the sales department of the focal firm engages potential customers/investors, they can advertise the benefits of their vertical integration strategies, demonstrating how fast design iteration and concurrent engineering abilities alleviate early risk for their new technology. This idea was inspired during the interview phase of this thesis: "I don't think people (investors) are scared of new technology, what people are scared of is risk (technical risk), and the reason why new technology […] gets overshadowed, is that often, [..] companies present these new innovative ideas, but they don't present how they're going to mitigate their risks" (A. Vargas, personal communication, 4/15/2022). This unaccounted risk can be identified in early mutually corresponding development stages and holds especially true for technology stemming from extraordinary research. "The importance of reciprocal rather than sequential modes of interdependence appears to be greatest at the fuzzy front-end of product development, especially to the extent designs are novel" (Liker et al. 1999, p. 249). Therefore, developing good cross-functional policies within a firm, as well as retaining tight control over design and interface standards when incorporating external suppliers into the product value chain, enables quick iterative design practice and accelerates parallel path opportunities for early risk mitigation (Liker et al. 1999, 251, 253). When deployed for novel innovative energy technology, combining these vertical integration strategies will tend to minimize R&D costs, reduce project

[7] Supplier behavioral uncertainty describes opportunistic decisions suppliers may make such as unexpected renegotiations or resetting terms in their own favor. See: Williamson 1985, as cited by Adner and Kapoor 2010, p. 327 in *Value creation in innovation ecosystems*

risk, and ensure good design standards that later enable modularity and easy form-factor changes, furthering the goal for widespread standardization of the new technology.

Figure 15: Depiction of vertical integration by system for complex hardware products



Source: Own representation

In realizing the ETIS framework concerning economies of scale and scope for new energy technologies, it's apparent that specialization and standardization play fundamental roles. Firms that pursue development efforts in niche markets can amortize costs over larger or more complex products as well as exploit pre-existing R&D structures within the local supplier community. Equally important, catalyzing standardization with modular design practices and vertical integration strategies; firms that constitute these policies can shift eventual mass production likelihoods in their favor. Whether the policies include enforcing compatibility standards that create interoperability for their technologies or establishing internal cross-functional teams while employing external supplier risk mitigation techniques, the firm can expect "to realize economies of scale and scope as well as [..] reduce time and costs associated with extensive R&D processes" (Hagedoorn 1993, as cited by Veer et al. 2016, p. 5)

2.2.3 The Roles of Actors and Institutions

The significance of non-risk-averse players is at the core of the ETIS perspective. In the early phases of new energy innovation, technological uncertainty is high. Many actors collectively work through these uncertainties in an environment influenced by the institutions surrounding them. Learned patterns of behavior establish the institutionalized environment with rules, regulations, routines, and norms (Grübler et al. 2012, p. 1688), not unsimilar to a Kuhnian paradigm. ETIS authors convey a sense of changing institutional conditions over historical periods in which learning and unlearning, driven by the actors, are essential for systematic evolution in solving new challenges (2012, p. 1688). Interestingly in an analogous way, Kuhn describes this institutional change as a paradigmatic cycle driven by anomalies or crisis in normal patterns of scientific activities (instead of economic) (1970, 102–103, 123). A solution, Kuhn writes, are "the extraordinary investigations that lead the profession at last to a new set of commitments, a new basis for the practice of science" (1970, p. 18). The researchers practicing extraordinary science are not unlike the entrepreneurs described in ETIS. Throughout the next paragraphs I will investigate the role of entrepreneurs in relation to novel energy innovation, as well as the concept of shared expectations as a strategic innovation tool. Lastly, I will discuss government and private actor's roles in supporting these entrepreneurs in an environment of uncertainty.

Perceived uncertainty is the minimization problem for the entrepreneur. In this view, uncertainty is subjective and depends on how an individual organizes and evaluates stimuli in their environment (Corrêa 1994, as cited by Meijer and Hekkert 2007, p. 284). In the domain of extraordinary research, technological uncertainty is perceived by the entrepreneur, either be it uncertainties in performance, cost, or infrastructure adaptability characteristics (Meijer and Hekkert 2007, p. 284). Decisions must be made to reduce these uncertainties. "For example, if an entrepreneur perceives high technological uncertainty about an innovative technology, the entrepreneur can either decide to abandon investments or to experiment in order to learn about the new technology and, thereby, reduce uncertainty" (Meijer and Hekkert 2007, p. 285). The role of the entrepreneur is therefore not only to turn new knowledge into business opportunities (Grübler et al. 2012, p. 1688), but to also minimize their own and other actors perceived uncertainty through experimentation. "Experimenting by entrepreneurs is necessary to collect more knowledge about the functioning of the technology under different circumstances and to evaluate reactions of consumers, government, suppliers and competitors" (Hekkert et al. 2007, as cited by Meijer and Hekkert 2007, p. 286). Experimentation is therefore integral to the entrepreneurs activities, to the process of knowledge generation, and to eventual spillover (Grübler et al. 2012, p. 1688) as described in 2.2.1. These investigations typically require extended periods of time during their formative phase and subsequently benefit from policies and external actors that support them.

Shared expectations are one example of strong sociological policy drivers that stimulate entrepreneurial activities. Having a promising 'vision' of the future technology with identified use-cases can be seen as the foundation of these expectations (Stewart et al. 1999, as cited by Pollock and Williams 2010, p. 527). Since the merits of NET cannot be known in advance, the authors of ETIS suggest shared expectations can help mobilize support and funding for the experimentation journey (Grübler et al. 2012, p. 1689; van Lente 1993, as cited by Pollock and Williams 2010, p. 527). Support generation is a topic that starts transcending into realms of game theory[8], but in general, entrepreneurs must have a 'script' for their expectations. The script tells a story about the "promising lines of research and technical development to be undertaken" and allows outside actors to assess via examining priorities and strategic orientations relative to the script. If these actors agree and there is mutual perceived uncertainty, intentions, and interests, then their support is garnered (van Lente and Rip 1998, 18, 22). Here, it's also worth mentioning the warning around articulation of script. Mobilizing support should not be accomplished by creating 'hype' and setting unreasonable expectations for NET; else, the risk for disastrous damage to the entrepreneur's credibility as well as the entire innovation field (Borup et al. 2006, as cited by Pollock and Williams 2010, p. 529), a point which will be elaborated further in Section 3.3. "Not only do expectations help enrol external actors [...] they are also seen to guide and shape the activities of technology development teams. They do so, as van Lente (1993) argues, through providing structure and legitimation to an inherently uncertain activity" (Pollock and Williams 2010, p. 527). This can be seen through the influence of shared expectations created at the governmental level. For example, the EU's public 2030 electric vehicle goals to reduce carbon emissions has sparked electrification shifts to many major auto manufactures (Bateman 2021). Other examples like the policies around existing renewable energy technologies (solar, wind, etc.) promote and shape societal preferences to realize desired objectives (Gallagher et al. 2012, p. 143). Shared expectations like these "help build consensus both about what to expect and on the nature of the various opportunities and risks that lay ahead" (Borup et al. 2006, as cited by Pollock and Williams 2010, p. 528).

While long term policy decisions by government actors can certainly improve the innovation environment for entrepreneurs, they can also inadvertently lead to technological lock-in. Supporting only incremental innovation and setting stable technological trajectories as has been

[8] Development of shared expectations can create a self-fulfilling prophecy in which actors act on the shared promise leading to *prisoner's dilemma* situations. See: van Lente and Rip 1998, p. 4 *Expectations in technological developments*

seen in the carbon lock-in of electricity regimes (Raven 2007, p. 2391; Unruh 2000). Over time, this locking out of alternatives enables a "certain 'hardness' to a system, which often represent large vested interests of incumbent actors" (Walker 2000, as cited by Raven 2007, p. 2391). Again, an effect somewhat analogous to a Kuhnian paradigm. To address lock-in, Raven (2007) and others have categorized solutions into three levels of perspectives:

1. Early niche market deployment (Kemp and Rip 1998)
2. Technological niches[9] (Kemp and Rip 1998; Hoogma et al. 2002; Raven 2005)
3. Socio-technical landscape[10] (Raven 2007)

All of which encompass the principal of adaptive policy making in response to feedback. Openness to policy change requires "policy-makers to take a broader perspective on the opportunities for learning and innovation and to pay greater attention to innovation in [small to medium-sized enterprises] (SMEs)" (Mytelka 2000, p. 19). Innovation systems that encourage dynamic policy creation can also force investors to rethink technological lock-in trajectories; deepening investment hesitation towards incremental improvement of legacy technologies (Raven 2007, p. 2397). Furthermore, the relationship between innovation and regulation is reciprocal and warrants adaptation of regulation content to changing entrepreneurial environment conditions (Paraskevopoulou 2012, p. 1059). Through dynamic policy-making in areas including "subsidies, tax incentives, regulated feed-in tariffs, procurement policies, minimum production quotas, and exemptions from regulation" (Raven 2007, as cited by Gallagher et al. 2012, p. 143), lock-in risks can be mitigated, attracting entrepreneurs to a fairer playing field.

From the investment perspective, while there is some public sector market formation, most activity is seen in the private sector. According to ETIS, three main asset classes measure this activity (Gallagher et al. 2012, p. 147):

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[9] When early niche markets do not exist, markets for the new innovations have to be created such that there is a co-evolution of the space with input from innovators, users, policy-makers, and industrial actors (Raven 2007, p. 2391). See Kemp and Rip 1998 *Technological Change. In: Rayner, S., Malone, E.L. (Eds.), Human Choice and Climate Change*; Hoogma et al. 2002 *Experimenting for Sustainable Transport*; Raven 2005 *Strategic Niche Management for Biomass*

[10] The Socio-technical landscape perspective "highlights the role of events and developments in the exogenous environment: developments and events that cannot be controlled by regime or niche actors. It is a rather descriptive concept that refers to broad societal trends such as macro-economic developments (e.g., recessions, global oil prices)" (Raven 2007, p. 2391). See Raven 2007 *Niche accumulation and hybridisation strategies in transition processes towards a sustainable energy system*

1. Venture capital/private equity (VC/PE)
2. New listings on public markets
3. Asset finance

There is substantial evidence to show how these asset classes have historically contributed to new energy commercialization; however, there are several caveats. Obtaining large investments through asset finance and new listings are typically reserved for more mature technologies (solar, wind, etc.) and VC/PE investors are usually focused on projects that bear fruit early and are less interested in longer term novel technology investments (Gallagher et al. 2012, p. 147; Rosenburg 2010, as cited by Gallagher et al. 2012, p. 149). Another concern is private, government, or institutional actors lacking the knowledge and expertise to validate a group claiming extraordinary technology (Coopersmith 2016, 138, 140). Addressing the latter two points, firstly, rather than partnering with incompatible VC/PE, novel energy deployment should associate with investors whose policies on market sectors are somewhat decoupled from economic turmoil and recession to smooth out investment patterns as innovation requires sustained and steady inputs (Gallagher et al. 2012, p. 149). "Second, there are formidable data problems associated with the description of energy innovation, especially for the [...] private sector. This gap calls for a renewed effort in innovation data collection and sharing, without which public policy risks navigating either blind or one-eyed (Gallagher et al. 2012, p. 149). Here, the ETIS authors are referring to lack of information and understanding on supply and end-use of energy technology investments, but I intend to also make this statement apply for firms that mislead investors with extraordinary claims, a topic that will be examined further in Section 3.3.

The many barriers to market entry as highlighted in the previous sections make risky business for entrepreneurs and investors alike. With the right strategies though, and ideas from literary findings, a model for reducing entrepreneurial environment uncertainty can be deployed by the entrepreneur as well as external actors. Rigorous experimentation minimizes perceived uncertainty for all actors involved while at the same time creating realistic shared expectations. These build confidence in policy strategies and helps legitimize the technology over time. Although not directly alluded to so far in this paper, support of unbiased knowledgeable advocacy groups[11] can also help inform external actors regarding the importance of adaptive policy making (Grübler et al. 2012, p. 1689). Shedding light on technological lock-in risks can shift policy changes to favor novel technologies. Furthermore, with the right expertise, these advocacy groups can support technology legitimization and through this, help embed entrepreneurs within recession-decoupled market sector networks. As an additional remark, advocacy groups should present a script that emphasizes economic growth and prosperity, championing fundamental human needs through reducing cost of energy access, improved reliability & security, and reduced environmental pollution (Gallagher et al. 2012, pp. 149–150). A script that most governments would be receptive to.

2.3 Quality Function Deployment

Measuring potential quality impact can be constitutive to the planning phase of new products, especially to the extent designs are novel. Here, the history and developments of quality function deployment (QFD) are reviewed as well as a new QFD method used in this paper for evaluating novel technologies.

2.3.1 History of QFD

In the late 1960's Professors Shigeru Mizuno and Yoji Akao formulated a new management approach called quality function deployment that would incorporate quality into a products design. At the time, quality control methods were secondary, only considered during or after product launch (Mazur 2018). By applying assurance methods into the QFD structure, parametrizing aspects like customer needs and satisfaction, market research, and technical specifications would lay the foundations for new QFD tools (Wolniak 2016, p. 127; Mazur 2018). Later in 1972, Mitsubishi Heavy Industry applied QFD into a new design planning tool for an oil tanker project at Kobe Shipyards. Known as the 'house of quality' (HOQ), this tool "is a kind of conceptual map that provides the means for interfunctional planning and communications" (Hauser and Clausing 1988, p. 1). This was the first time the Japanese firm practically deployed the structured format of HOQ and marked the start of QFD popularization.

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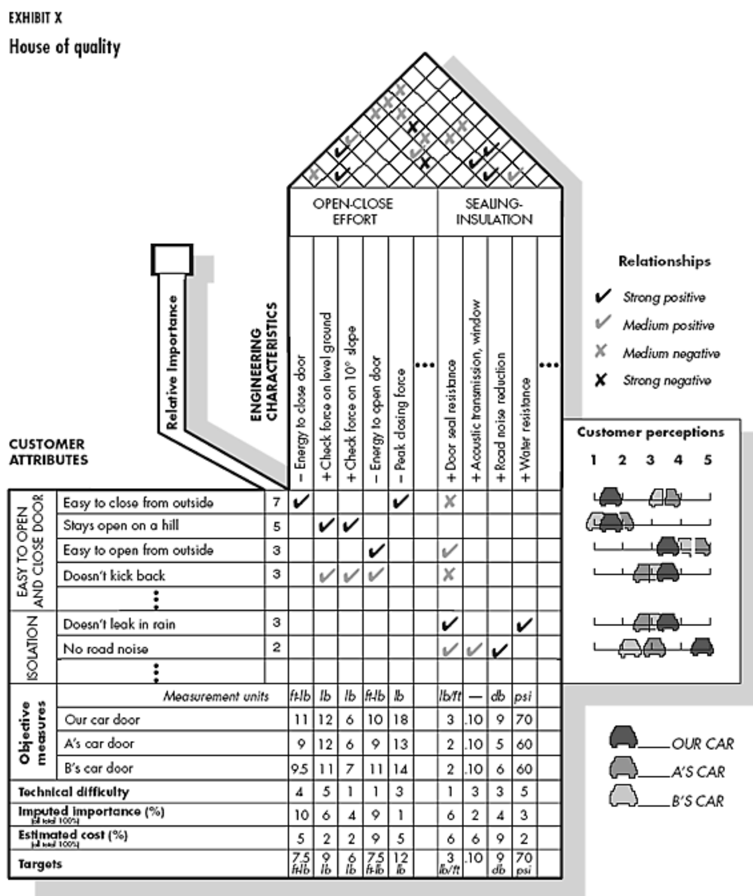
[11] Examples of novel energy advocacy groups:

- UnLab: https://unlab.us/
- Society for Scientific Exploration: https://www.scientificexploration.org/
- Integrity Research Institute: https://www.integrity-research.org/
- Hathaway Research International: https://www.hathawayresearch.com/

Figure 16: House of Quality example



Source: Hauser and Clausing (1988)

By 1983, QFD had spread to America and Europe, catching the attention of a wide variety of industries (Akao and Mazur 2003, p. 23). This knowledge spillover sparked new innovations to the QFD field "generating ever new applications, practitioners and researchers each year" (Mazur 2018). Today, modern QFD tools are used around the world and help firms manage product innovation through the unveiling of customer needs. Whether the innovation is a product, process, or service, QFD brings early awareness to the management team, highlighting the voice of the customer with appropriate market segmentation, opportunity and positioning considerations (Wolniak 2016; Killen et al. 2005, pp. 21–22). Moreover, QFD enables management to choose from a range of "strategic initiatives that are coherent and mutually supportive", selecting the technical and organizational ideas that minimize implementation risks and deliver the identified customer-centered innovations (Killen et al. 2005, pp. 23–24).

2.3.2 QFD Developments

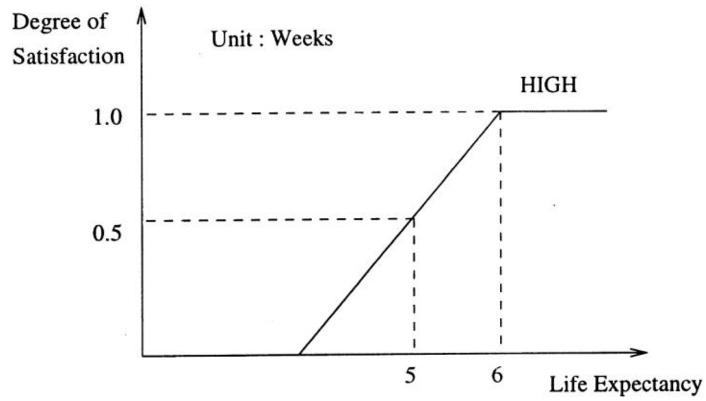
From the HOQ perspective, running a QFD analysis primarily requires answers to the following questions (Schuster 2019):

1. Who are the customers?
2. What are their needs/wants?
3. How well are the customers satisfied now?
4. How to measure if the needs are met?
5. How much is good enough performance?

Pondering on these questions, the management team can align on the best customer requirements and translate the requirements into technical specifications that an engineering team can comprehend (Temponi et al. 1999, p. 341). The technical specifications, otherwise known as Engineering characteristics (ECs), "should describe the product in measurable terms and should directly affect customer perceptions" (Hauser and Clausing 1988, p. 7). Hauser and Clausing (1988, pp. 7–8) state that studies, surveys, expert experience, or controlled experiments help build consensus on ECs while filling out the HOQ matrix. They further emphasize that during this process, careful consideration should be given to each EC; hasty justification can lead to vagueness, yielding indifference to the needs customers have. The authors point to patient and systematic analysis for each EC to minimize trivial characteristics from sneaking in and artificially limiting creativity. When well executed, creating an HOQ result matrix enables less-biased debate regarding design priorities as stakeholders can develop their arguments by sourcing patterns of evidence from the matrix (Hauser and Clausing 1988, p. 1).

The successes with HOQ processes have been widely documented; however, mixed experiences and failures have also been reported by firms (Griffin and Hauser 1993, as cited by Temponi et al. 1999, p. 341). Early implementations of QFD have struggled with the subjective nature of customer needs (CNs) and have incentivized researchers to evaluate new methods. "Generally speaking, customers' description of their ideal product is neither precise nor systematic; very often, it is rather fuzzy with a lot of redundancy. Hence, customer requirements have to be reviewed, analysed, qualified and classified" (Wang and Ma 2007, p. 231). Described in detail by Temponi et al. (1999), this common problem of HOQ is the lack of precision in the semantics of natural language; interpretation issues around what customers mean when they express fuzzy phrases like: "'high competition', 'low interference', 'low impact', or 'high collaboration'" epitomizes the problem. (Hisdal 1988, as cited by Temponi et al. 1999, p. 341). To address these quantification issues, the authors propose a fuzzy logic approach in which a systematic analysis on linguistic terms are mapped through membership functions into corresponding customer requirements. Figure 17 illustrates an example membership function.

Figure 17: An example HIGH membership function



Source: Temponi et al. (1999)

By an identification and reasoning scheme, the fuzzy terms mapping exposes conflicting CNs and helps discover implicit relationships between CNs. Such schemes, create an effective tool for teams to build consensus and save time (Temponi et al. 1999, 346, 349). Kwong et al. (2007) built upon this work with their proposed methodology of developing a fuzzy expert system[12] to measure the importance of ECs while still considering the relational importance of corresponding CNs (2007, p. 669). Their research extrapolates ideas from Tang et al. (2002) and Chen et al. (2004) whereby importance measures of ECs were considered in the formulation of those mathematic programming models. Other QFD developments by Wang and Ma (2007) investigate a comprehensive optimization and consolidation of QFD techniques from past literature. They cite the work of Fung et al. (1998), (2002) in which the relationships between CNs and ECs are expressed as a hybrid system utilizing QFD principals, fuzzy logic, and Analytic Hierarchy Process (AHP)[13]. Specifically, the enhancements

[12] " Fuzzy expert systems consist of fuzzification, inference, knowledge base and defuzzification subsystems, and uses fuzzy logic, instead of Boolean logic, to reason about data in the inference mechanism" (Liao 2003, as cited by Kwong et al. 2007, p. 670). See Kwong et al. 2007 *A methodology of determining aggregated importance of engineering characteristics in QFD*

[13] "AHP is a multiobjective, multicriterion decision-making approach which employs a pairwise comparison procedure to arrive at a scale of preferences among sets of alternatives". The setup requires the unstructured problem to be broken down into its component parts numerically and into a hierarchic order (Saaty 1984, p. 286). See Saaty 1984. *The Analytic Hierarchy Process: Decision Making in Complex Environments*

to this structure include an Analytic Network Process (ANP)[14] for CN and EC importance ranking, an overlap analysis for qualification of CNs, a new correlation and filtering method for ECs and CNs, and consideration of influential factors on ECs such as cost, lead-time, and resource limitations through a Zero-One Goal Programming (ZOGP)[15] approach (2007, pp. 230–236). All considered, this methods advantages create a QFD system that is more verifiable and explicit, developing better correlations, qualifications, and selections of CNs and ECs (2007, p. 236). Yet, certain shortcomings arise in all these QFD approaches when data availability and quality limitations subvert practicality.

2.3.3 Concept Design Analysis

While fuzzy logic and new CN weighting and correlation techniques have made strides in solving underlying problems in practical QFD tools, difficulties remain due to lack of accurate qualitative data as well as the time-consuming tasks of filling in large HOQ matrices (Temponi et al. 1999; Mazur 2018). These problems are further unassailable when products contain novel technologies and only conceptual designs can be examined. Some might argue that a QFD type analysis shouldn't be considered at such an early design stage, but according to Blanchard (1978) "about 75% of the life-cycle costs of any product are determined by the design decisions made during the conceptual design stages" (as cited by Eres et al. 2014, p. 66). The limited data availability during preliminary design activities encouraged researchers Woolley et al. (2000), (2001), and Feneley et al. (2003) to develop an enhancement to QFD. The concept design analysis (CODA) model is the culmination of their work and was used extensively by Eres et al. (2014) in the paper: *Mapping customer needs to engineering characteristics: an aerospace perspective for conceptual design*. Like traditional QFD, CODA uses CNs and ECs as endogenous inputs. Relationally mapped together, these inputs help designers systematically assess the value generated by improving the customer satisfaction levels (2014, pp. 71–72). By modifying tangible and measurable ECs, designers can immediately "perform a wide range of analyses, such as trade-off and what-if studies, sensitivity analysis, and engineering design optimization" (2014, p. 72). Unlike linear fuzzy logic mem-

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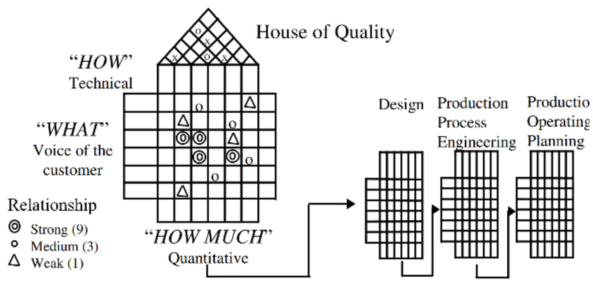
[14] Very similar to AHP, ANP also uses pairwise comparisons of constituent parts, but rather than a hierarchic order, a network structure is implemented with feedback mechanisms. See Saaty 1996. *Decision making with dependence and feedback: The analytic network process*

[15] ZOGP is a decision tool to help measure deviation from a given a set of desired goals. From this, optimal ECs may be determined. See Karsak et al. 2003 *Product planning in quality function deployment using a combined analytic network process and goal programming approach*

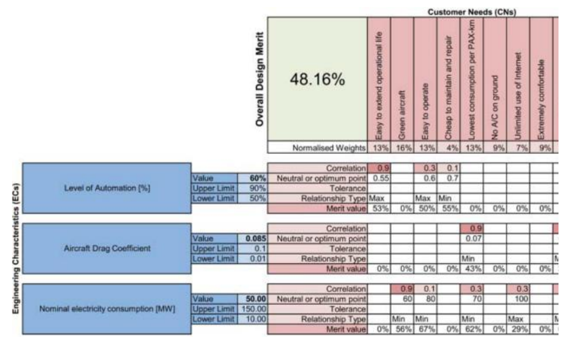
bership functions (recall figure 17), CODA represents customer satisfaction through non-linear functions allowing better capture of complex CN behaviors (2014, p. 68). Furthermore, contrasting the typical 4-matrix HOQ QFD analysis in figure 18, CODA uses only a single matrix to calculate an overall design merit (ODM) score, saving time for designers. Figure 19 showcases a completed CODA ODM matrix.

Figure 18: 4-Matrix QFD process



Source: Woolley et al. (2000)

Figure 19: CODA ODM matrix



Source: Eres et al. (2014)

The more simplistic approach helps CODA fit better within data availability restrictions in early designs compared to other QFD approaches (2014, p. 68); therefore, in this paper, the CODA methodology will be used to assess the merits of NETs on a customer needs basis for various technologies and applications.

3 Methodology

3.1 Overview

In the proceeding sections, the application and technology selections, both existing and novel, are articulated as well as the CODA procedure. Starting with 3.2, ETIS driven market sector and application selections are justified and partially address this papers research question. Next, Section 3.3 explores questions around legitimate NETs and finalizes the choices for this paper. In 3.4, the interviews and interview process combined with the CODA procedure are described in step-by-step format showcasing an interactive CODA automation tool that enables interview efficiencies. Finally, in Section 3.5, a CODA comparative method is explained that foreshadows novel technology benchmarking against existing/baseline solutions. NET EC estimations that are needed for this benchmarking are developed further in the results section.

3.2 Market Sector and Application Selection

Identifying ideal novel energy deployment through key ETIS drivers for existing or new firms was the main purpose of Section 2.2. Therefore, in this section, I adopt compatibility criteria described by ETIS to justify a selection of market sectors and applications. The compatibility criteria originate within the previously described perspectives: 2.2.1 knowledge and learning, 2.2.2 economies of scale and scope, and 2.2.3 the roles of actors and institutions. The market sectors examined in this paper through these compatibility perspectives are space, agriculture, and air transportation.

3.2.1 Space

Space, the final frontier, is a specialized market and provides many reasons for its potential in developing NET. Accompanying the highly niche industry are projects that tend to be complex, expensive, or physically large, opening up the ability to amortize costs as described in 2.2.2. Compatible with knowledge spillover, an emerging trend can be seen in the European space sector in which new startups entering the market are more embracing of knowledge sharing through open innovation which is a stark contrast to traditional space industry (Summerer 2009, p. 12). In the U.S., "[t]he growth and evolution of [these] new entrants have been driven by small satellite technologies" (Yonekura et al. 2022, p. v) as well as in the European market (Summerer 2011, p. 136). University departments and research centers have strongly influenced small satellite technology development, due to the realized usefulness of small-scale efficiencies[16] (Summerer 2009, p. 11). By assimilating universities into the space market, minimization of knowledge depreciation is maintained through the ETIS ideas discussed in 2.2.1. Documentation is also crucial for lowering turn-over risks, which in the space industry, due to the stringent certification requirements, high documentation standards are required. In addition to amortization and knowledge drivers, novel technology can scale through modularization. Based on an expert interview in which a cube satellite (CubeSat) application was discussed, ease-of-integration was a top customer need in which modularity was the key solver (Q. Mannes, personal communication,

[16] "Compared with traditional spacecraft, these are one to two orders of magnitude smaller and less massive, less reliable, with shorter lifetimes, simpler and faster in their construction and design and orders of magnitude cheaper" (Meerman and Sweeting 2002, as cited by Summerer 2009, p. 11). See Meerman and Sweeting 2002 *20 Years Experience with using Low Cost Launch Opportunities for 20 Small Satellite Missions*

22/3/2022). Finally, regarding the roles of external actors in the space sector, it is apparent the dominance of government programs (Summerer 2011, p. 127). Through these programs offers the opportunities for things like adaptive policy changes, long term funding for experimentation, and technology legitimization; all of which new and mature firms can benefit. Therefore, taking all these ETIS modes of compatibility into consideration, the specific applications explored in this paper are power systems for two CubeSats as well as a power system for a robotic arm used on commercial space stations for servicing satellites.

3.2.2 Agriculture

The agriculture industry, specifically the equipment manufacturers, also fall into the niche market category with some specialized equipment only selling from a few hundred to a few thousand units per year. The low volumes and high complexity create many opportunities for amortization of new technologies. For instance, a state of the art John Deere combine harvester can sell for well over 1 million USD (Hardy 2020). Other ETIS compatible features for the agriculture sector include patent and IP protections, standardization through vertical integration strategies, and economic turmoil decoupling. IP protections were found to encourage technology transfer via increased imports/exports of agricultural equipment, thereby increasing economic growth of the sector and inadvertently improving knowledge accumulation and spillover (Lippoldti 2015, p. 14). Vertical integration strategies employed by equipment manufacturers have also generated numerous benefits. The tighter control of their value chains has led to faster innovation cycles, and increased customer satisfaction thereby expanding operations and diversifying business models (Saroniemi et al. 2022). All of which are standardization drivers. Interestingly, the agriculture sector can also be recognized as a safe haven for innovation. Chen et al. (2020) have shown that improvements in mechanization and technology in the agricultural sector have contributed to energy-efficient farming, effectively decoupling agriculture from Gross Domestic Product (GDP) growth in countries with these advancements. Since the access to energy is heavily linked to an economy’s health, countries with low agricultural energy consumption that experience economic turmoil can better sustain agricultural innovation. With these compatibility metrics, NET has good potential to develop in the agricultural equipment environment. Therefore, the application analyzed in this paper is a John Deer X911 Combine Harvester engine.

3.2.3 Air Transportation

Since the Wright brothers first flew in 1885, air transportation has been a pinnacle of human innovation (Grant 2017). Compact power systems have enabled longer and further flight times while advanced system architectures have improved safety and redundancy. This system complexity makes air transportation another market in which the ability to amortize costs is beneficial for new technologies. Safety and redundancy requirements have enforced strict documentation practices during the technical design of aircrafts (Sghairi et al. 2008), compatible with minimizing knowledge depreciation. Regarding modularity, companies like Airbus have been seeking to reduce complexity of their systems by creating more "independent modules linked by more or less standardised and stable interfaces" (Frigant and Talbot 2005, p. 344). For the aircraft interview partner in this paper, a unique and even more niche application was explored. Electric Flytrain is a relatively new startup that specializes in advanced electric propulsion systems. One of their projects, and a focus in this paper, is an emergency helicopter power system. Using an electric motor and batteries is a first in the industry for this application. Compatible with knowledge spillover and standardization, the startup is currently in talks with another major aircraft firm to develop common standards for the emergency system (T. Kahnert, personal communication 15/3/2022). Their partnerships with other geographically local aircraft firms have also proved to be a big advantage as the access to critical lab equipment allows larger more representative experimentation. Furthermore, although small, the company is structured with horizontal lines of communication reducing project risks with fast communication feedback channels. For these reasons and others, the aircraft manufacturing sector is an ideal candidate for developing NET within.

Table 2: Summary of market sector and application selections

Market Sector	Application	Technology
Space	CubeSat Power System #1	Lithium Batteries + Solar
Space	CubeSat Power System #2	Lithium Batteries + Solar
Space	Robotic Arm Power System	Lithium Batteries + Solar
Agriculture	X911 Combine Harvester Power System	Diesel Engine
Air Transportation	Emergency Helicopter Power System	Lithium Polymer Batteries

Source: Own representation

3.2.4 Additional Compatibility Perspectives

Although not mentioned in their respective paragraphs, there are several overarching ETIS traits common among the market selections. Historically, energy systems have been confined to slow rates of innovation "with technological transitions spanning several decades up to a century" (Gallagher et al. 2012, p. 140). Therefore, these markets were chosen due to their resilience to past, present, and future obsolescence, providing the time needed for novel technologies to develop. In addition, the complex and innovative nature of these markets and applications necessitates experimentation which further evolve R&D structures and processes, allowing easier alignment with extraordinary energy research. Although the ETIS authors make no reference to the types of NETs discussed thus far in this paper, the key features and drivers of their system are well grounded throughout the cited literature and are compatible with space, agriculture, and air transportation. Hence, the selected market sectors and the applications therein, satisfy the first part of this papers research question: **Given a selection of market sectors and applications…** and thereby sets this papers scope to evaluate the relative merits of novel and existing energy technologies on a customer needs basis.

3.3 Selecting Novel Energy Technologies

Claims of extraordinary NETs have been pervasive since the popularization of the internet. Thousands of misleading videos online peddling 'perpetual motion' for views or entertainment along with hundreds of fraudulent energy startups creating hype and swindling investors pockets. These actions have tainted the entire ZPE research community with skepticism and made funding for legitimate research hard to come by. How then should NETs be chosen for a technology comparison, as was referred to in this papers research question? During a lead-user interview with the founder of Hathaway Research Institute, this problem was discussed at length. The issue seems to be the lack of accountability by inventors or entrepreneurs spewing claims on the internet (G. Hathaway, personal communication, 4/22/2022). Many of these actors may even have sincere intentions but are blinded by overconfidence and underestimation of technological uncertainty (Coopersmith 2016, p. 139); a false confidence not managed by any outside pressure. On the other hand, inventors associated with academia are naturally more cautious in managing uncertainty with the stakes being their personal academic credibility. Furthermore, novel technologies described in published papers typically have basis in reasonable theories, although be it in a paradigm not widely accepted by the broader scientific community. A point which is to be expected according to Thomas Kuhn. Therefore, only technological claims that have a history of academic publications will be explored in this paper, of which were previously introduced in Section 2.1. The technological choices here may also serve as a standard for future novel energy market innovation research. Table 3 overviews the technologies.

Table 3: Novel energy technology selections

Novel Energy Technology	Firm / University	Primary Physics Models	Results Published?
Graphene Harvester	University of Arkansas	Newtonian / Brownian Motion	Yes
MIM + Optical Casimir Cavity	University of Colorado	Quantum Electrodynamics / Stochastic Electrodynamics	Yes
Ferroelectric Oscillator	Quantum Power Munich GmbH	Quantum Electrodynamics	No

Source: Own representation

3.4 CODA Methodology

The primary role of CODA is to provide project management teams with an efficient tool for quickly evaluating merit of new design concepts. In this paper, I take this a step further and build upon the CODA process demonstrated by Eres et al. (2014) and Khamuknin et al. (2015). Through experimental structuring of an interview process and a newly developed CODA automation tool, I show a faster cadence for completing a CODA, describe an alternative step-by-step CODA process, and lastly explain how the output of CODAs can be conceptually compared to each other as a method to answer this papers research question.

3.4.1 Interview Process

Two categories of experts were interviewed during this research: industry experts and lead users. For establishing a baseline for the merits of novel technologies, industry experts participated in developing an overall design merit (ODM) score for their respective power system applications with existing technologies. In the first round of interviews, interviewees were explained the high-level CODA process and shown examples of CNs and ECs. Through this, relevant CNs and their weightings were chosen. Second and third follow up interviews focused on EC selection and merit curve parameterization and are explained in detail in the next section. Industry expert interviews and correspondence are summarized in table 4.

Table 4: Industry expert interviews / correspondence

Date	Name	Title / Function	Firm	Technology / Application	Interview Type	Interview Length
2/8/2022	T. Kahnert	Founder	Electric Flytrain GmbH	Emergency Helicopter Power System	Zoom	60min
2/9/2022	Q. Mannes	Lead Engineer	Bradford Space	CubeSat Power System #1	Zoom	30min
2/18/2022	G. Pope	Staff Engineer	John Deere	X911 Combine Harvester Power System	Zoom	75min
3/9/2022	T. Kahnert	Founder	Electric Flytrain GmbH	Emergency Helicopter Power System	Zoom	60min
3/15/2022	T. Kahnert	Founder	Electric Flytrain GmbH	Emergency Helicopter Power System	Zoom	45min
3/22/2022	Q. Mannes	Lead Engineer	Bradford Space	CubeSat Power System #1	Zoom	60min
3/29/2022	J. Aerts	Senior Engineer	Hiber Space	CubeSat Power System #2	Zoom	60min
4/1/2022	G. Pope	Staff Engineer	John Deere	X911 Combine Harvester Power System	Zoom	80min
4/15/2022	A. Vargas	Project Engineer	MDA Space	Robotic Arm Power System	Zoom	110min
5/13/2022	J. Aerts	Senior Engineer	Hiber Space	CubeSat Power System #2	Zoom	60min
6/07/2022	A. Vargas	Project Engineer	MDA Space	Robotic Arm Power System	Zoom	80min
6/10/2022	A. Vargas	Project Engineer	MDA Space	Robotic Arm Power System	Zoom	45min

Source: Own representation

Originally, von Hippel's *Lead Users: A Source of Novel Product Concepts* (1986) provided inspiration for the lead-user interview process. Loosely structured, the interviews were designed to obtain intuitive insights on new and leading-edge novel energy information with the intent of eventually obtaining EC values for baseline CODA comparisons. The information obtained from lead-users was invaluable; even so, it became clear that gathering EC data matching baseline EC constraints proved too challenging, with some lead users only providing minimal information and declining to interview. The main concern being the underdeveloped nature of the novel technologies, a point later addressed in detail in Sections 3.5 and 4.2. Table 5 summarizes the lead user interviews and correspondence.

Table 5: Lead user interviews /correspondence

Date	Name	Title / Function	Firm / University	Technology / Application	Interview Type	Interview Length
1/13/2022	T. Valone	Founder	Integrity Research Institute	Spiral Magnetic Motor	Zoom	100min
2/1/2022	M. Reid	Founder	Quantum Power Munich GmbH	Ferroelectric Crystal Oscillator	In Person	120min
3/28/2022	D. Danzik	Director	Inductance Energy	Earth Engine	Email	0min
4/6/2022	P. Thibado	Professor	University of Arkansas	Graphene Harvester	Email	0min
4/20/2022	G. Moddel	Professor	University of Colorado	MIM + Optical Casimir Cavity	Email	0min
4/22/2022	G. Hathaway	Founder	Hathaway Research Institute	General – ZPE Research	Telephone	50min
5/12/2022	M. Reid	Founder	Quantum Power Munich GmbH	Ferroelectric Crystal Oscillator	In Person	120min
6/24/2022	M. Reid	Founder	Quantum Power Munich GmbH	Ferroelectric Crystal Oscillator	In Person	120min

Source: Own representation

3.4.2 CODA Process

The CODA methodology employed in this paper can be described in seven steps:

1. Identifying CNs
2. Prioritizing CNs
3. EC parameterization
4. CN-EC correlation strength mapping
5. Selecting functional relationship type
6. Merit curve mapping/parameterization
7. ODM calculations

1. For identifying CNs, Eres et al. (2014) suggest individual surveys, customer focus groups, or expert panels as sources; however, due to limited time and access to experts, CN sources were constrained to a single industry expert per application. During the first interview, the experts were encouraged to provide the most important top 5 to 10 CNs they could conceptualize based on their experience developing the power system. CNs such as *must be lightweight*, or *ease of integration* are some such examples.

2. Different CNs have different levels of influence, or importance weight (Wang and Ma 2007). Several methods appear in literature (discussed in 2.3.2) for ranking the importance of CNs such as AHP and ANP. Though these methods capture higher resolution in CN

weightings, they require more effort and longer deliberation time, aspects which were not feasible for this thesis's research. Therefore, a binary weight matrix (BWM) procedure, also used by Eres et al. (2014), was chosen. This method only requires the interviewee to choose between a binary number for CN prioritization and results in quick decisioning between CNs. Figure 20 displays a BWM table in which a 1 is chosen when the CN in the left-most column is more important than the CN in the uppermost row. Once all pairwise prioritizations are performed, the normalized scores are calculated using equation (3).

Figure 20: Binary weight matrix for CubeSat power system #1

Cube Satellite Power System	Must be lightweight	Ease of integration testing	Should be highly efficient	Needs to have a medium lifetime (finish mission)	Must have good radiation resilience	Heritage (knowledge reuse)	x - scores	y - scores	total score	Biased Score	Normalized Score
Must be lightweight		1	0	1	0	0	2	0	2	3	14.3%
Ease of integration testing			1	0	0	0	1	0	1	2	9.5%
Should be highly efficient				0	0	0	0	1	1	2	9.5%
Needs to have a medium lifetime (finish mission)					1	1	2	2	4	5	23.8%
Must have good radiation resilience						0	0	3	3	4	19.0%
Heritage (knowledge reuse)							0	4	4	5	23.8%
	0	0	1	2	3	4	5	10	15	21	100.0%

Source: Own representation (based on Eres et al. (2014))

$$N_i = \frac{X_i + Y_i + 1}{\sum_{i=1}^{M}(X_i + Y_i + 1)} \quad (3)$$

Where X_i is the row sum of 1's and Y_i is the column sum of 0's.

3. Next, in follow up interviews the experts were asked to describe the ECs that relate and have an effect in solving the CNs. It was ensured that all CNs had at least one EC with a determinable relationship. Lower and upper limits were defined for each EC and a value was chosen that best represented an actual power system design specification.

Figure 21: EC parameterization example

Engineering Characteristics (ECs)		
Power System Weight (kg)	Value	**2.50**
	Lower Limit	0.00
	Upper Limit	4.00

Source: Own representation (based on Eres et al. (2014))

4. After EC parameterization, each EC was correlated with all CNs. The interviewee was asked if there is a strong (0.9), medium (0.3), weak (0.1), or no correlation (0.0) between the CN-EC paring. In some instances, to ensure interview efficiency, pre-interview draft CN-EC correlations were intuitively filled in, that then only needed to be fined tuned or modified by the industry expert.

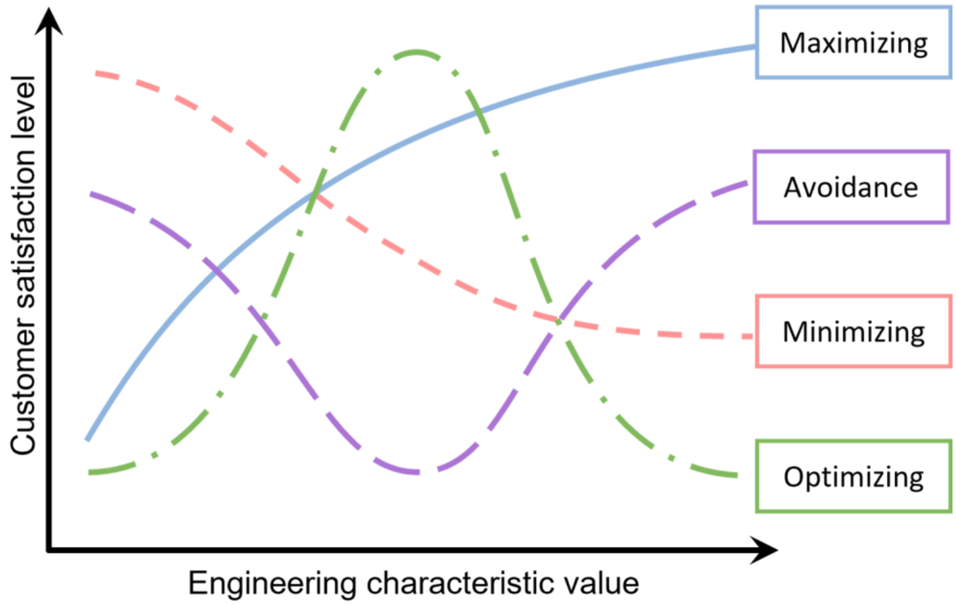
Figure 22: CN-EC correlation strength mapping

			CN #1	CN #2	CN #3	CN #4	CN #5	CN #6
		Correlation	0.3			0.1	0.9	
EC Value	**0.20**	Function Type						
Lower Limit	0.00	Neutral or Optimum Point						
Upper Limit	1.00	Tolerance						
		Power						
		Merit Value						

Source: Own representation (based on Eres et al. (2014))

5. A core foundation of CODA are the unique merit functions it defines. Shown in figure 23, these four function types describe the variation in customer satisfaction with respect to a CN as an EC value increases or decreases. The function type options presented here encourage interviewees to reason about the CN-EC relationship mappings and help bring new insights surrounding the importance of different ECs and their less tangible aspects.

Figure 23: Merit curve types



Source: Own representation (based on Eres et al. (2014); Khamuknin et al. (2015))

Defined by the equations below, every CN-EC relationship requires assignment of one of these non-linear mapping functions:

$$\text{Minimizing:} \quad f_{\text{min}}(\rho) = 1 - \frac{1}{\alpha^{\eta/\rho}} \tag{4}$$

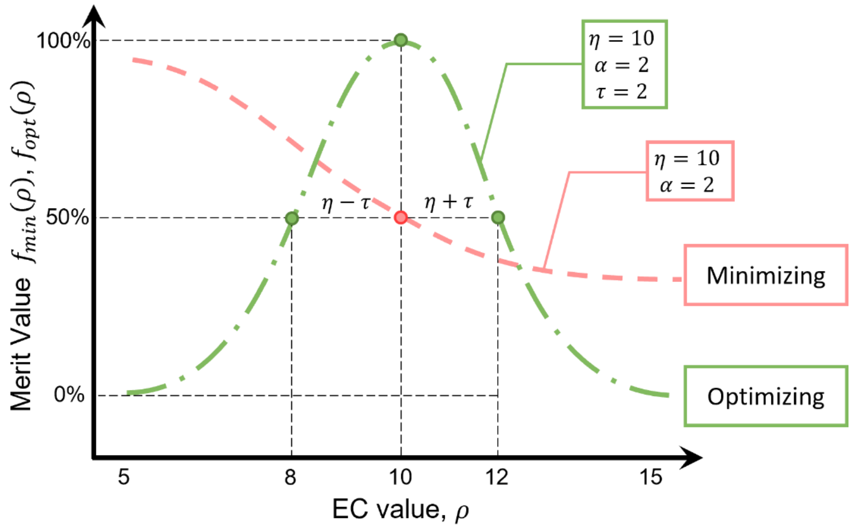
$$\text{Minimizing:} \quad f_{\text{max}}(\rho) = 1 - \frac{1}{\alpha^{\rho/\eta}} \tag{5}$$

$$\text{Optimizing:} \quad f_{\text{opt}}(\rho) = \frac{1}{1 + \left(\frac{|\rho - \eta|}{\tau}\right)^{\alpha}} \tag{6}$$

$$\text{Avoidance:} \quad f_{\text{avoid}}(\rho) = 1 - \frac{1}{1 + \left(\frac{|\rho - \eta|}{\tau}\right)^{\alpha}} \tag{7}$$

Here, for f_{min} and f_{max} function types, ρ is the value of the EC and η is the neutral point (Eres et al. 2014). η modifies the overall merit curve such that when $\alpha = 2$ and $\eta = \rho$, a 50% customer satisfaction or merit is recorded for that CN-EC relationship. Likewise, for f_{opt} and f_{avoid}, ρ is also the value of the EC, but η instead represents the optimal point or 100% customer satisfaction when $\alpha = 2$ and $\eta = \rho$. Another variable τ is also used here to describe the tolerance or width of the bell-shaped curves as illustrated in figure 24. Normally, the power variable α is statically fixed at 2; however, based on early interview experiences, it became desirous to control this parameter to adjust curve steepness in some instances.

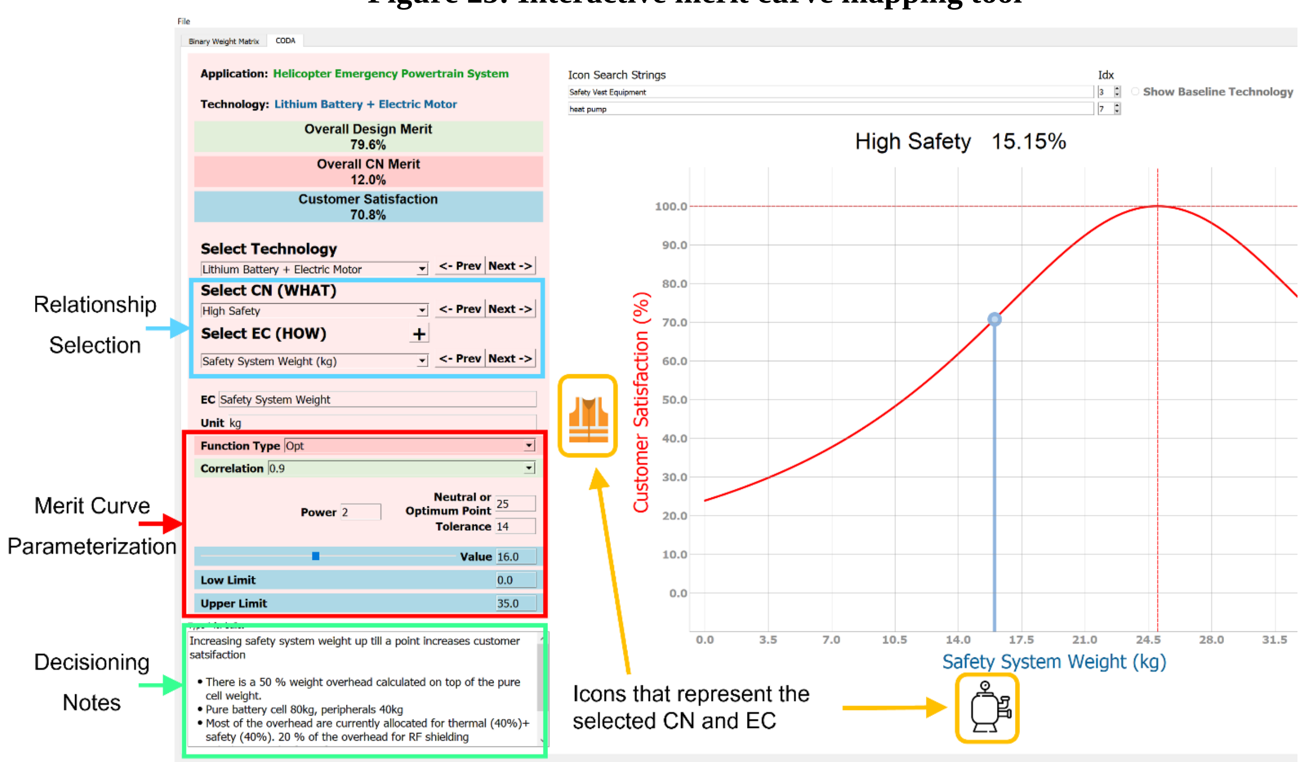
Figure 24: The effect of neutral point η, tolerance, τ, and power, α, on merit curves



Source: Own representation (based on Eres et al. (2014))

6. With the understanding that the number and length of interviews would be limited, an interactive CODA automation tool was developed with Python to improve function type and merit curve decisioning efficiency. This tool imports previously defined CNs, BWM, and CN-EC correlations (.xlsx) and graphically displays parametric controls for each merit curve.

Figure 25: Interactive merit curve mapping tool



Source: Own representation

Using this tool during the interview process, merit curves were seamlessly defined for the CN-EC relationships and extensive amounts of time was saved relative to attempting the process in a simple spreadsheet.

7. After merit curve decisioning, the tool automatically calculates the customer satisfaction (CS) scores of each CN following equation (8).

$$CS_i = \frac{N_i}{SCF_i} \sum_{j=1}^{N} MV_{ij}(\rho_j) \cdot CF_{ij} \tag{8}$$

If there are N ECs, then $MV_{ij}(\rho_j)$ is the function defining the merit value of each EC's parameter value. This merit value is multiplied together with the corresponding correlation factor CF_{ij} (0.0, 0.1, 0.3, or 0.9) previously assigned to each EC, the sum of which is normalized by the CN's weight N_i over the sum of correlation factors SCF_i. Finally, for M number of CNs, the ODM score is as follows:

$$ODM = \sum_{i=1}^{M} CS_i \tag{9}$$

The tool exports a CODA .xlsx with all merit curve values updated as exemplified below.

Figure 26: Example CODA output

Technology		Overall Design Merit (ODM)	80.5%	CN #1	CN #2	CN #3	CN #4	CN #5	CN #6
			Normalized Weights	14%	10%	10%	24%	19%	24%
Engineering Characteristics (ECs)									
EC #1			Correlation	0.9	0.1				
	Value	2.50	Function Type	Opt	Avoid				
	Lower Limit	0.00	Neutral or Optimum Point	0.00	8.00				
	Upper Limit	4.00	Tolerance	3.30	3.81				
			Power	4.00	8.00				
			Merit Value	75.2%	95.0%				
EC #2			Correlation	0.3			0.3	0.9	
	Value	0.20	Function Type	Opt			Max	Opt	
	Lower Limit	0.00	Neutral or Optimum Point	0.00			0.09	0.20	
	Upper Limit	1.00	Tolerance	0.40				0.20	
			Power	2.00			2.00	2.00	
			Merit Value	80.0%			80.1%	100.0%	

Source: Own presentation (based on Eres et al. (2014))

3.5 CODA Benchmarking Method

The flexibility of CODA enables a wide range of analyses. Typically, designers will use CODA for design optimization within a new product or benchmark their concept to already existing competing products. The analysis employed here is situated somewhere in the middle. By completing CODAs for already optimized and existing designs, an ODM baseline can be established to contrast and compare NETs to. Discussed in Section 5.2, not only will the relative merits on a customer needs basis be compared, but new design trends regarding novel technology ODM performance when viewed against different power system applications will be revealed.

As mentioned earlier, to complete this analysis, the EC values for novel technologies should be chosen within the EC ranges of the baseline CODAs. Ideally, the EC values should be informed by lead user interviews, but for multiple reasons, limited EC data exists and requires an estimation procedure instead. Addressed further in Section 4.2, information taken from literature, online video presentations/interviews, and patents, assist in the EC estimation process. After estimations are complete, the ODM calculations are straight forward. For each baseline application only EC values are updated, leaving the merit curves how industry experts defined them. Some risk in over or under estimating EC values exists, but with thorough research, realistic EC values can be obtained resulting in new ODM scores for the novel technologies under different applications.

4 Results & Findings

4.1 Baseline Technologies Analysis

Following the CODA method, five different technology analyses were generated resulting in five ODM scores. Each ODM score is governed by the CNs, ECs and BWM prioritizations characterized by each industry expert independently. This section covers in detail the findings of these prioritizations. For brevity purposes, only one full CODA will be analyzed in the next subsections; the remaining CODAs are available in Appendix 8.2 of this report.

4.1.1 CN and BWM Results

As described in Section 3.4.2, a BWM is completed first to give each CN a relative weighting. During this process, many insights were gained about what is important in a power system application from a CN perspective and these findings are mentioned briefly in this section. Additionally, the binary decision-making aspect of BWM sometimes proved challenging to fill out, but by the end of the exercise, each industry expert voiced high satisfaction with the final normalized CN scores. In Section 3.4.2, figure 20 depicts a final BWM for the CubeSat power system #1 application. The remaining application BWM figures can be viewed in Appendix 8.1. Table 6 showcases the final CNs and BWM results for all applications.

Table 6: Customer needs and their importance

Market Sector	Application	Customer Need	Importance
Space	CubeSat Power System #1	Must be lightweight	14.3%
		Ease of integration testing	9.5%
		Should be highly efficient	9.5%
		Needs to have a medium lifetime (finish mission)	23.8%
		Must have good radiation resilience	19.0%
		Heritage (knowledge reuse)	23.8%
Space	CubeSat Power System #2	Must be lightweight	19.0%
		Good operating life	23.8%
		Good power profile over orbit	23.8%
		Easy to certify	4.8%
		Low Earth magnetic field influence	19.0%
		High Technology Readiness Level (TRL)	9.5%
Space	Robotic Arm Power System	Must meet weight requirements	19.4%
		Long operating life	8.3%
		Excellent thermal cycling survivability	13.9%
		High versatility (varying load conditions)	8.3%
		Must meet volumetric requirements	8.3%

		High redundancy (multiple independent systems)	22.2%
		High Serviceability	11.1%
		High Technology Readiness Level (TRL)	8.3%
Agriculture	Combine Harvester Power System	High versatility	15.6%
		High reliability	13.3%
		High fuel efficiency	8.9%
		Good machine data accuracy	4.4%
		High temp high altitude efficiency	4.4%
		High combustibility resistance	15.6%
		Should have easy maintenance	4.4%
		Must meet volumetric requirements	17.8%
		Must meet required energy balance	15.6%
Air Transportation	Emergency Helicopter Power System	Good med/high energy content	9.1%
		High power	13.6%
		High safety	15.2%
		High one-time use reliability	13.6%
		Long shelf life	6.1%
		Very low operating temperature	7.6%
		Good vibration resistance	12.1%
		High altitude operation	6.1%
		High shock resistance/survivability	7.6%
		Good external radiation protection	6.1%
		Water and particle ingress protections	3.0%

Source: Own representation

For the CubeSat power system applications, several cross-over CNs are worth highlighting. Both satellite experts (Q. Mannes; J. Aerts, personal communication, 2/9/2022, 3/29/2022) assigned a high weighting to *operational life / mission completeness* and the requirement for being *lightweight*, needs that ultimately relate to energy density and reliability characteristics. Other similar CNs between the two include *heritage* and *high technology readiness level*[17] (TRL) addressing the underlying expectations that a chosen technology inherits efficiencies from previous experience in operation. Some of these requirements are also echoed in the robotic arm power system application and motivate several ECs presented in the next sub-section. Contrasted to the CubeSats, the robotic power system is larger and has more functional requirements driving its complexity. Therefore, CNs such as *high versatility*,

[17] TRL is a tiered measurement system to gage the maturity level of a specific technology. See: https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level (retrieved 6/16/2022)

redundancy, and *serviceability* help inform the correct ECs for such complexity. (A. Vargas, personal communication, 4/15/2022). In the case of a combine harvester power system, the CNs selected are generally driven by a high versatility principal. Firstly, by the CNs that enable versatility (*volumetric* and *energy balance* requirements) and secondly by *versatility* itself. The motives behind this principal stem from decades of feedback from agrarian producers. "[Farmers] just want to get in a machine that works every day, unchanged, from crop to crop, all day long, and across the whole season" (G. Pope, personal communication, 2/18/2022). From a power systems standpoint, this statement translates to CNs governing a system that should be *highly fuel efficient*, have *good reliability*, *flame retardant*, and have enough power to handle a wide range of crop conditions (2/18/2022). Juxtaposing versatility, Electric Flytrain's emergency helicopter power system needs to do only one thing and do it very well. Civil helicopters predominantly used over city airspace require a back-up power system providing five minutes of emergency flight time. Safety, therefore, is the primary perspective for this application and reinforces many of the chosen CNs. Focuses include *high safety*, *high power*, and *one-time-use reliability* (T. Kahnert, personal communication, 2/8/2022).

4.1.2 EC Parameters

In follow-up interviews with the industry experts, ECs, their ranges, and values were chosen. Table 7 consolidates the parameters used for the baseline technologies in their respective applications.

Table 7: Engineering characteristics, ranges, and values

Application	Baseline Technology	Engineering Characteristic	Range	Value
CubeSat Power System #1	Solar + Lithium Ion Battery	Power system weight (kg)	0-4	2.5
		Radiation shielding weight (kg)	0-1	0.2
		Power efficiency (%)	0-100	95
		Knowledge reuse (%)	0-100	50
		Mission completeness (%)	0-100	95
		Modularity (%)	0-100	50
CubeSat Power System #2	Solar + Lithium Ion Battery	Power system weight (kg)	0-8	1.5
		Available avg power output (W)	0-100	25
		Power efficiency (%)	0-100	90
		Net magnetizable material mass as percentage of total weight (%)	0-100	5
		Life expectancy (years)	0-10	3
		Average sub-component TRL (TRL)	1-9	7

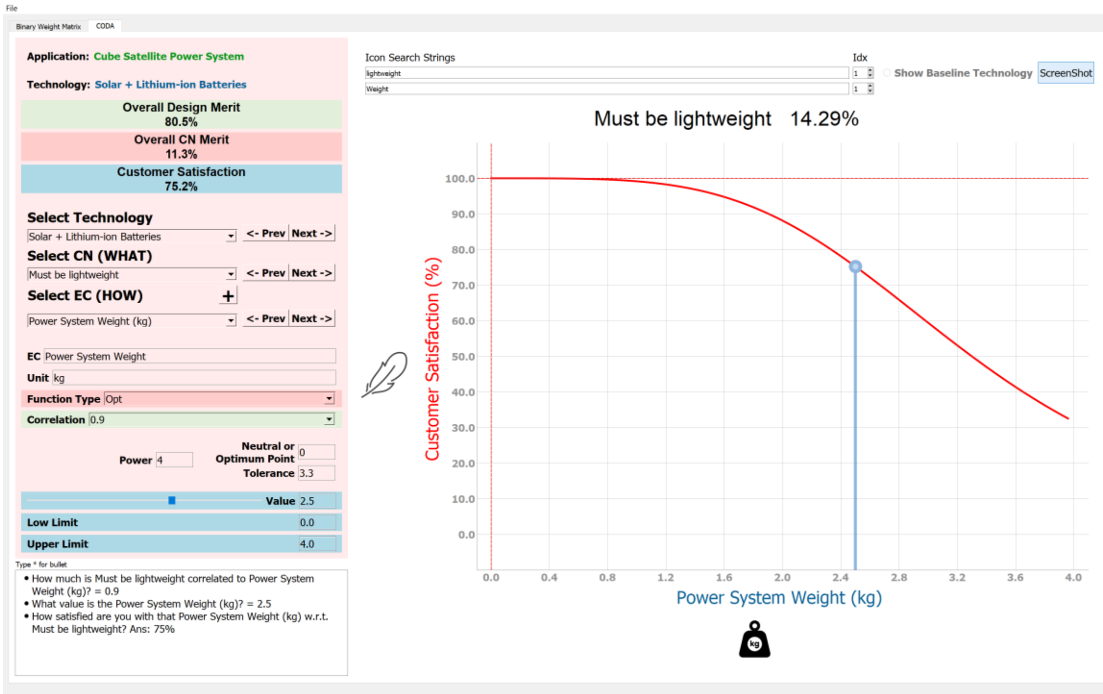
		Number of high-risk materials (# of materials)	0-5	1
Robotic Arm Power System	Solar + Lithium Ion Battery	Weight (kg)	50-500	350
		Operating life (years)	8-20	15
		Mechanical complexity (# Parts)	20-200	50
		Temperature (Delta C)	100-200	150
		Number of power bus lines (# bus bars)	2-10	5
		Volume (m^3)	0.03-10	3.38
		Robotically serviceable mass (%)	0-100	10
		Probability of achieving >= 8 TRL after 3 years (%)	0-100	75
		Probability of achieving >= 8 TRL after 18 months (%)	0-100	60
		Fault tolerance design (# faults)	1-8	2
		Power output (W)	200-10e3	1750
Combine Harvester Power System	Diesel Engine	Weight goals (kg)	4e3-7e3	6000
		Versatility index (%)	0-100	85
		Power (kW)	200-700	455
		Altitude rating (feet)	0-7e3	4500
		Avg consumable fuel input (liters/hour)	0-200	89
		Failure rate (MTBF-hours)	0-2e3	500
		Sensor reporting index (Coverage-Idx*Bandwidth-Idx)	0-1	0.38
		Use of advanced materials (%)	0-100	50
		Tribal knowledge (%)	0-100	80
		Volumetric (m^3)	0-9	7.5
Emergency Helicopter Power System	Lithium Polymer Battery	Power system weight (kg)	0-200	80
		RF shielding weight (kg)	0-16	8
		Safety system weight (kg)	0-25	16
		Thermal system weight (kg)	0-32	6
		Specific power rating (W/kg)	0-10e3	8000
		Energy density (Wh/kg)	0-300	150
		Inches per sec rating (IPS)	0-2.5	2
		Failure rate (MTBF-hours)	1e3-150e3	100e3
		Expected shelf life (years)	0-15	10
		Component rating confidence (%)	0-100	70
		Shock rating (g's)	0-60	30
		Rated altitude (kPa)	50-150	55

Source: Own representation

The ECs of baseline technologies represent ‘the how’ for addressing CNs. In the CubeSat applications, prioritizations were given to metrics that help quantify validation and certification times through ECs such as *modularity*, *knowledge re-use*, *sub-component TRL*, and the *number of different high-risk materials*. Other ECs focus on the effectiveness against external environmental factors and help measure probability of mission success. Characteristics like *radiation shielding weight* supports power system reliability, or *net magnetizable material mass* as a % of total weight minimizes the amount of energy needed to counteract Earth's magnetic field influence for orientation corrections (Q. Mannes; J. Aerts, personal communication, 3/22/2022, 5/13/2022). Relative to CubeSats, for a robotic arm power system, the use-case time horizons are significantly different with 5 to 10 times longer missions. To ensure long term survival in a space environment, more emphasis was given to include ECs that measure technology readiness of the robot via intricate system design rather than ECs focused on project timing. Accounting for the *number of power busses* at different voltages, percent of *robotically serviceable mass*, or *the number of faults* that can occur before a catastrophic failure, encapsulate this survivability intent (A. Vargas, personal communication, 6/7/2022). In a similar fashion, the combine harvester ECs also portrayed focus on survivability but under the context of versatility. By improving the values of ECs such as *versatility index*, *altitude rating*, *failure rate*, *use of advanced materials*, and *company knowledge*, overall improved power system versatility is realized. To state one example, the requirement for combustibility resistance has a strong relationship with the *use of advanced materials*, implying that the integration of more fireproof materials in the power system design may reduce machine downtime (G. Pope, personal communication, 4/1/2022). Regarding the emergency helicopter power system, as stated previously, the theme driving the chosen ECs is safety. To meet this goal, most ECs focus on reliability test metrics such as *shelf-life*, *shock*, *IPS*, *altitude* and *failure ratings*. Due to the intense instantaneous power demand for this application, *thermal* and *safety system weights* were separated from *power system weight* to allow better disambiguation of CN-EC mappings. Since the power system was still in development during the writing of this paper, concepts like *component confidence rating* were also included to cover a broad assessment of parts that have not finished reliability qualification. (T. Kahnert, personal communication, 3/9/2022, 3/15/2022).

4.1.3 ODM Scoring

Figure 27: Merit curve decisioning for CubeSat power system #1



Source: Own representation

In the same or in additional follow up interviews, merit curve decisioning was performed for each CN-EC mapping. First, each relationship was mapped with a correlation factor, then, using the interactive tool as described in 3.4.2, merit curves were established to best describe the expert's satisfaction for various EC values. Figure 27 illustrates a merit curve mapping. After all merit curves are defined, a final CODA matrix is generated by the tool. Figure 28 showcases the CODA for the CubeSat power system #1. The remaining application CODAs can be viewed in Appendix 8.2 of this report.

Figure 28: CODA matrix for CubeSat power system #1

Solar + Lithium-ion Batteries			Overall Design Merit (ODM): 80.5%	Must be lightweight	Ease of integration testing	Should be highly efficient	Needs to have a medium lifetime (finish mission)	Must have good radiation resilience	Heritage (knowledge reuse)
			Normalized Weights	14%	10%	10%	24%	19%	24%
Engineering Characteristics (EC's)									
Power System Weight (kg)			Correlation	0.9	0.1				
	Value	**2.50**	Function Type	Opt	Avoid				
	Lower Limit	0.00	Neutral or Optimum Point	0.00	8.00				
	Upper Limit	4.00	Tolerance	3.30	3.81				
			Power	4.00	8.00				
			Merit Value	75.2%	95.0%				
Radiation Shielding Weight (kg)			Correlation	0.3			0.3	0.9	
	Value	**0.20**	Function Type	Opt			Max	Opt	
	Lower Limit	0.00	Neutral or Optimum Point	0.00			0.09	0.20	
	Upper Limit	1.00	Tolerance	0.40				0.20	
			Power	2.00			2.00	2.00	
			Merit Value	80.0%			80.1%	100.0%	
Power Efficiency (%)			Correlation	0.3		0.9			
	Value	**95.00**	Function Type	Opt		Opt			
	Lower Limit	0.00	Neutral or Optimum Point	100.00		110.00			
	Upper Limit	100.00	Tolerance	12.00		30.00			
			Power	2.00		4.00			
			Merit Value	85.2%		94.1%			
Knowledge Reuse (%)			Correlation	0.1	0.1	0.1	0.3	0.1	0.9
	Value	**50.00**	Function Type	Max	Max	Max	Avoid	Avoid	Max
	Lower Limit	0.00	Neutral or Optimum Point	25.00	36.00	50.00	0.00	0.00	25.00
	Upper Limit	100.00	Tolerance				50.00	41.60	
			Power	2.00	4.00	2.00	6.00	6.00	2.00
			Merit Value	75.0%	85.4%	50.0%	50.0%	75.1%	75.0%
Mission Completeness (%)			Correlation				0.9		
	Value	**95.00**	Function Type				Opt		
	Lower Limit	0.00	Neutral or Optimum Point				110.00		
	Upper Limit	100.00	Tolerance				20.00		
			Power				8.00		
			Merit Value				90.9%		
Modularity (%)			Correlation	0.1	0.9				0.3
	Value	**50.00**	Function Type	Opt	Opt				Opt
	Lower Limit	0.00	Neutral or Optimum Point	50.00	100.00				100.00
	Upper Limit	100.00	Tolerance	30.00	81.20				40.00
			Power	2.00	2.00				2.00
			Merit Value	100.0%	72.5%				39.0%

Source: Own representation (based on Eres et al. (2014))

During these analyses, the reasoning process for selecting correlations and merit curves are quite nuanced and cannot be easily captured in written form. To take one example from figure 28, power efficiency is mapped with the CNs *must be lightweight* and *should be highly efficient*. The latter is directly obvious; however, more knowledge is required to understand the correlation to *must be lightweight*. Excess heating while in direct sunlight drives the need for power efficiency as there is a direct consequence to power system heat-sinks adding weight (Q. Mannes, personal communication, 3/22/2022). This type of back-and-forth discussion process with experts is critical to obtaining realistic CN-EC mappings and provides more accurate ODM scores. Table 8 shows the final ODM scores for the baseline technology applications.

Table 8: Baseline technology ODM scores

Market Sector	Application	Technology	ODM
Space	CubeSat Power System #1	Solar + Lithium Ion Battery	80.5%
Space	CubeSat Power System #2	Solar + Lithium Ion Battery	78.2%
Space	Robotic Arm Power System	Solar + Lithium Ion Battery	83.4%
Agriculture	Combine Harvester Power System	Diesel Engine	67.6%
Air Transportation	Emergency Helicopter Power System	Lithium Polymer Battery	79.6%

Source: Own representation

4.2 Novel Energy Technologies Analysis

The challenge of evaluating merit between novel and existing technologies is rendered clear by the fact that the novel technologies are still in very early development phases. Sometimes, even the lead-user experts themselves can only speculate about how reliable their technology will be or the various architectures and form factors that may be available in future iterations. Therefore, in this section I propose three levels of sources for reasonably estimating the engineering characteristic values. Table 9 summarizes these levels and allocates a notation that will be carried over into the next sub-sections EC tables.

Table 9: Engineering Characteristic Source Notation

Sources	Notation
Experimental Results or Expert Opinion	*
Directly Comparable Applications/Technologies	**
Indirectly Comparable Applications/Technologies	***

Source: Own representation

Experimental results and expert opinions provide the clearest picture of what the technology is currently capable of and are sourced as much as possible when available. Directly comparable applications represent a moderate to high level of technology association defined as >50% shared characteristics and operational environments. Indirectly comparable technologies share some important traits but have <50% common aspects, qualifying a low to moderate level of comparability. Essentially, as the EC source becomes more abstract, the error bars on each estimation would increase. The size of these error bars is outside the scope of this paper, but the dynamic structure of CODA enables easy what-if studies for inquisitive readers to check potentially over-optimistic EC estimations.

4.2.1 Power Density ECs

For NETs, power density characteristics play a determining role in measuring their competitiveness with existing technologies. From the selections in 3.3, two of the three technologies lack competitiveness in their current 2D form factor and compel further analysis into the third dimension. According to Moddel (2022, t=40:20), based on observed experimental results "there's no reason we can't go into the 3rd dimension". Since these two technologies are both semiconductor based and follow comparable manufacturing processes used in the commercial semiconductor industry, I apply findings from 3D integrated circuit research and extrapolate wafer stacking possibilities as a multiplier for power density. Table 10 details the assumptions taken for the power density ECs.

Table 10: Power density derivation by 3D wafer stacking

Metric	Graphene Harvester	MIM + Optical Casimir Cavity	Ferroelectric Oscillator
Quad Flat No-Lead (QFN) Package (mm)	5x5 * [a]	7x7 ** [b]	-
Package height (mm)	1.50 ** [c]	1.50 ** [d]	-
Wafer stackable height (WSH) (mm)	1.20 ** [c]	1.20 ** [d]	-
Weight per mm^3 (mg)	2.62 ** [c]	2.37 ** [d]	-
Device weight (mg)	98.33 ** [c]	192.73 ** [d]	-
Number of devices per m^2	40000	20408	-
Weight per m^2 (kg)	4.30 ** [e]	3.92 ** [f]	-
Wafer thickness (µm)	5.00 ** [g]	20.00 ** [h]	-
Number layers per device (WSH/wafer thickness)	240 ** [i]	60 ** [i]	-
Power density single layer (W/kg)	0.23 * [j]	17.85 * [k]	-
Power density multi-layer (W/kg)	**55.81** **	**1071.43** **	**1000.00** ** [l]
Volumetric power density multi-layer (kW/m^3)	**96.00** ** [m]	**1680.00** ** [m]	**4065.00** * [n]
Density (kg/m^3)	**1720.00** **	**1568.00** **	**7500.00** * [n]

Source : Own representation

[a] Experimental device is 5x5mm package (Thibado 2022), therefore, comparable reference devices (59mg): https://eu.mouser.com/ProductDetail/STMicroelectronics/ST25R3911BAQFT?qs=pBOFM1sAujv0291w1NR1FA%3D%3D; https://eu.mouser.com/ProductDetail/NXPSemiconductors/MC32PF1550A4EP?qs=BZBei1rCqCDxOARPCAz4hw%3D%3D (both retrieved on 5/23/2022)

[b] Reference device (116mg): https://eu.mouser.com/ProductDetail/TexasInstruments/CC1020RSST?qs=sGAEpiMZZMv2aFJto%252B5bBRoUmriupFY6K2N4n%2FbEHKo%3D (retrieved on 6/9/2022)

[c] Referring to *a*, reference devices have a package height of 0.9mm. Here, the device is proportionally scaled to 1.5mm to allow more wafer stacking. WSH based on 0.3mm potting encapsulation (Chen et al. 2018).

[d] Referring to *b*, reference device has a package height of 1.0mm. Here, the device is proportionally scaled to 1.5mm to allow more wafer stacking. WSH based on 0.3mm potting encapsulation (Chen et al. 2018).

[e] Weight of $40E^3$ devices ($3.93kg/m^2$) + weight of 0.2mm thick FR-4 board material at $1.85g/cm^3$ ($0.37kg/m^2$)

[f] Weight of $20.4E^3$ devices ($3.55kg/m^2$) + weight of 0.2mm thick FR-4 board material at $1.85g/cm^3$ ($0.37kg/m^2$)

[g] Based on wafer thinning processes and SOI technology, see paragraph below for further descriptions.

[h] Based on MIM cell design and thermal considerations, see paragraph below for further descriptions.

[i] 3D 'not and' (NAND) semiconductors already achieving 232-256-layers (Hilson 2022; Herh 2022).

[j] Based on $1W/m^2$ experimental results (Thibado and Kumar 2017; Thibado 2022): $1W/m^2$ / 4.30kg

[k] Based on $70W/m^2$ experimental results (Moddel 2020; 2022): $70W/m^2$ / 3.92kg

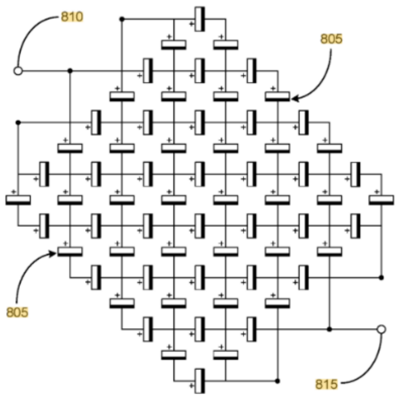
[l] Researchers' expectations (M. Reid, L. Lausin, personal communication, 5/12/2022) and the observed peak FEE current densities of $400A/cm^2$ (Airapetov et al. 1990, as cited by Rosenman et al. 2000).

[m] Device stacking 0.2mm(FR-4) + 1.5mm(QFN) + 0.8mm(air gap) 1000mm / 2.5mm = 400 layers per 1m

[n] FCO cells can be concentrically stacked within each other leading to high volumetric power density. See Appendix 8.4 for depiction. Material density also provided (M. Reid, personal communication, 6/24/2022)

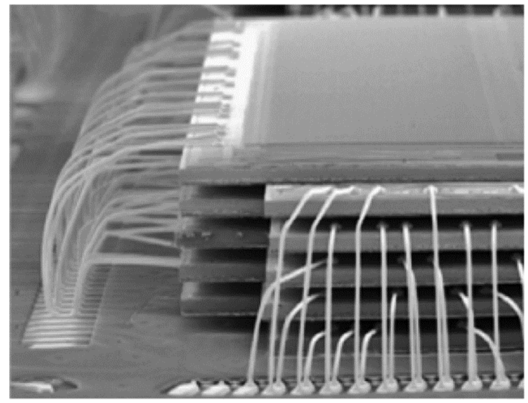
The wafer thicknesses defined in table 10 summarize findings from ultra-thin semiconductor process and 3D stacking literature. In 2006, International Business Machine (IBM) reported demonstrations of ~20μm wafer thinning through various manufacturing techniques (Topol et al. 2006, p. 496). Since then, significantly thinner wafers have been achieved. With through silicon via (TSV) formation and a silicon on insulator (SOI) process, stacking wafers <5μm can be realized (Garrou et al. 2011, p. 1). Researchers have furthermore demonstrated 2.6 μm thick capacitor circuits utilizing TSMC's 350 nm complementary metal-oxide semiconductor (CMOS) technology. Regarding the graphene harvester, according to the patent (Thibado and Kumar 2017), graphene sheet fluctuations at most require an open 100nm thick oscillation cavity to function. Therefore, with the accompanying capacitor diode circuitry and stated research findings, 5μm wafer layers may be obtainable. When assessing the MIM Casimir device however, due to the 70x higher power density relative to the graphene harvester, thermal effects should be considered for choosing a potential minimum wafer thickness. Pulling from the patent (Moddel 2020), figure 29 illustrates a potential configuration of many devices in series and parallel combination. Arrayed cell design in this way influences the internal cell resistance as well as the number of cell-to-cell interconnections, that if designed inefficiently could result in >50% of generated power dissipated in the connections (2020).

Figure 29: Array configuration of many series & parallel MIM devices



Source: Moddel (2020)

Figure 30: Wire bonded chips stacked in 3D package



Source: Garrou et al. (2011)

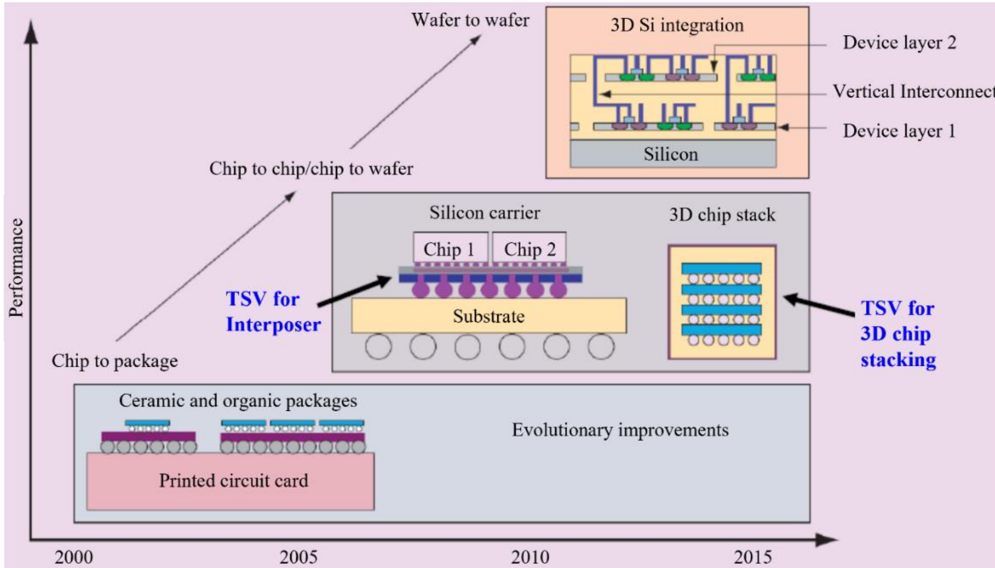
Considering this, I conservatively limit the wafer thickness to 20μm, leaving room for thermal conduction layers as well as ensuring losses produced in a 7x7mm package is below 0.170W. The standard junction temperature calculation in equation (10) supports this conclusion in a space environment 115℃ with no external thermal management system.

$$P_{max} = \frac{T_{J(\max)} - T_A}{\theta_J} = \frac{125 - 115}{58} = 0.172W\ ^{18} \quad (10)$$

Many challenges arise with 3D stacking thin wafers; increased joule heating leading to chip warpage and interfacial cracking causing electrical issues (Lancaster and Keswani 2018, p. 210). From figure 30, technical considerations such as alignment of layers and wire bonding techniques also require further research. Fortunately, the simplistic micro-structures of these energy harvesting devices enable larger alignment features and minimal circuit complexity, thereby increasing manufacturability and reliability to make 3D stacking more commercially viable. Figure 31 illustrates the forecasted technology roadmap for 3D circuits.

[18] See QFN handling and assembly document for further details on T_J, T_A Surface-mount QFN Package – Handling and Assembly (microsemi.com) (retrieved on 6/14/2022). For θ_J, an example CubeSat at 300K can at most dissipate 60W through 0.14m^2 (Hengeveld et al. 2018). ~350 devices fit in 0.14m^2. Therefore, a 7x7mm QFN package should not produce more heat than 60/350 = 0.172W. Results in a minimum θ_J = 58

Figure 31: IBM generic 3D technology roadmap



Source: Topol et al. (2006)

The layer densities forecasted in table 10 may seem overly ambitious; however, today, developments in 3D NAND technology have made major strides. Micron Technology has recently announced a 232-layer NAND chip slated to start production in 2023 (Hilson 2022), while analysts have revealed Samsung Electronics' plans for a 256-layer memory chip (Herh 2022). These technology developments pave the way for adoption into semiconductor based novel energy devices and warrant future investments.

4.2.2 Reliability ECs

Estimating reliability characteristics is rather challenging for new technologies. Many unforeseen variables may influence a power systems overall reliability. Even so, by finding reliability correlations with fully tested technologies, practical projections can be made.

Table 11: Reliability EC estimates

Reliability ECs	Graphene Harvester	MIM + Optical Casimir Cavity	Ferroelectric Crystal Oscillator
Inches Per Second Rating (IPS_{rms})	2.6 ** [o]	2.6 ** [o]	1.0 *** [p]
Shock Rating (g's)	1500 ** [q]	1500 ** [q]	500 *** [r]
Rated Altitude (kPA)	55 ** [s]	0 ** [t]	0 ** [t]
Failure Rate (MTBF-hours)	$1.0E^8$ ** [u]	$1.0E^8$ ** [u]	$1.7E^5$ **, * [v]
Operating Life (Years)	15+ ** [w]	15+ ** [w]	20+ * [x]
Temperature Delta Rating (Delta C)	125 ** [y]	125 ** [y]	100 * [z]

Component Rating Confidence (%)	70 ∗∗ [aa]	50 ∗∗ [aa]	90 ∗ [bb]
Expected Shelf Life (Years)	15+ ∗∗ [cc]	15+ ∗∗ [cc]	30+ ∗ [cc]

Source : Own representation

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[o] Based on automotive qualified semiconductors [AEC-Q101], validated devices in this way survive between 2.0 and 3.2 IPS_{rm}: http://www.aecouncil.com/Documents/AEC_Q101_Rev_E_Base_Document.pdf (retrieved on 6/14/2022)

[p] In piezoelectric oscillators, increased phase noise and output frequency shifts are experimentally confirmed at random vibrations above 1.4 IPSrms [MIL-STD-883H, Method 2026] (Li and Sridhar 2017). Furthermore, system reliability analysis of cantilever piezoelectric energy harvesters show resonant frequency fatigue failure above 0.6 IPSrms (Yoon and Youn 2019). See Appendix 8.4 for unit conversions.

[q] Based on automotive qualified semiconductors [AEC-Q101], validated devices in this way survive 1500 g's: http://www.aecouncil.com/Documents/AEC_Q101_Rev_E_Base_Document.pdf (retrieved on 6/14/2022)

[r] Normally, piezoelectric materials show high robustness against mechanical shock and vibration and are typically used as sensors to measure such tests. In the case of a FCO cell, sensitivity to phase criticality state and specific static stresses required for this state may negatively affect cell performance and thereby hinder shock and IPS ratings. Li and Sridhar (2017) show frequency shift effects with 500-g shock [MIL-STD-883H, Method 2002.5].

[s] As the graphene harvester is partially sourcing from thermal convection (Thibado et al. 2020), higher altitudes may affect power density performance.

[t] Semiconductors and piezoelectric/perovskite devices are generally unaffected by high altitudes disregarding needing increased thermal and radiation management.

[u] Typical MTBF for semiconductors is $1.0E^7$ to $1.0E^9$. From multiple sources: https://www.renesas.com/us/en/document/qsg/calculation-semiconductor-failure-rates; https://www.ti.com/quality/docs/estimator.tsp?partType=tiPartNumber&partNumber=CC1020RSST#resultstable (retrieved on 6/15/2022)

[v] Efforts to improve failure/degradation rate of perovskite solar cells are ongoing. Current research has reported minimal degradation with harsh thermal testing from $1.0E^3$ to $1.0E^4$ hours (Mazumdar et al. 2021). Since FCO cells don't encounter sunlight, and thermal shock can be attenuated via thermal management systems, much longer operational lives are expected [20 years * 8760hrs] (M. Reid, L. Lausin, personal communication, 6/24/2022).

[w] Modern semiconductor fabrication standards enable these operating lifetimes (Sperling 2016).

[x] Perovskite formulation is quite stable, early research devices have been running in laboratory for 20+ years (M. Reid, L. Lausin, personal communication, 6/24/2022).

[y] Standard temperature range for semiconductors is -40C to 85C.

[z] Operating temperature delta is similar to battery technology (M. Reid, personal communication, 6/24/2022).

[aa] Component confidence for AEC-Q100 semiconductors fall around 90% (Winter 2012); However, these novel devices have no reliability data. Component confidence is likely <70% for graphene device and <50% for MIM device.

[bb] These materials have had decades of serious military funding and testing; manufacturing processes are well understood to meet device specifications (M. Reid, personal communication, 6/24/2022).

[cc] For semiconductors, refer to *w*. For a FCO cell, long shelf life expected (M. Reid, L. Lausin, personal communication, 6/24/2022).

Generally, semiconductors fabricated by standard processes follow well documented reliability tests and results. Since the graphene and MIM devices also align with these manufacturing processes, directly comparable sources (∗∗) are used to estimate reliability ECs. In the case of an FCO, limited directly comparable technologies exist so metrics are mostly estimated from interviews with the researchers and indirect sources (∗, ∗∗∗).

4.2.3 Knowledge and Architecture ECs

Similarly, knowledge and architecture characteristic estimations rely on interviews and direct or indirect technology comparisons. For some ECs, the physical packaging sizes strongly impact the improved EC estimates. Smaller discretized form factors enable higher modularity and overall better sensor and system integration and improved serviceability; aspects which are not as feasible in physically larger power systems such as diesel engines or battery modules + solar arrays. Another group of ECs revolve around reusing knowledge to fast-track validation and development times. Various TRL forecasts, current and future, help quantify these concepts, of which, novel technologies experience disadvantages.

Table 12: Knowledge and architecture EC estimates

Knowledge & Architecture ECs	Graphene Harvester	MIM + Optical Casimir Cavity	Ferroelectric Oscillator
Versatility Index (%)	80 ∗∗ [dd]	90 ∗∗ [dd]	90 ∗∗∗ [dd]
Sensor Reporting Index (Coverage-idx * Bandwidth-idx)	0.81 ∗∗ [ee]	0.81 ∗∗ [ee]	0.60 ∗, ∗∗ [ff]
Tribal Knowledge or Knowledge Reuse (%)	70 ∗ [gg]	30 ∗ [hh]	10 ∗ [ii]
Mechanical Complexity (# parts)	40 ∗∗ [jj]	35 ∗∗ [jj]	45 ∗, ∗∗ [kk]
Use of Advanced Materials (% of total power system)	70 ∗∗ [ll]	70 ∗∗ [ll]	90 ∗ [mm]
Number of Power Bus Lines (# Lines)	4 ∗ [nn]	4 ∗ [nn]	4 ∗ [nn]
Robotically Serviceable Mass (% of total power system)	70 ∗∗ [oo]	80 ∗∗ [oo]	60 ∗, ∗∗ [pp]
Probability of achieving >= 8 TRL after 6 years (%)	75 ∗∗ [qq]	75 ∗∗ [qq]	90 ∗∗ [rr]
Probability of achieving >= 8 TRL after 3 years (%)	50 ∗∗ [qq]	50 ∗∗ [qq]	70 ∗∗ [rr]
Average Sub-component TRL (TRL)	2 ∗∗ [ss]	2 ∗∗ [ss]	3 ∗ [ss]
Fault Tolerance Design (# faults that lead to catastrophic failure)	2+ ∗ [tt]	2+ ∗ [tt]	2+ ∗ [tt]
Net Magnetizable Material Mass as percentage of total weight (%)	< 0.5∗∗ [uu]	< 0.5 ∗∗ [uu]	< 3 ∗ [uu]
Number of high-risk materials (# of materials)	0 ∗∗ [vv]	0 ∗∗ [vv]	0 ∗ [vv]
Modularity (% of total power system weight)	80 ∗∗ [ww]	80 ∗∗ [ww]	50 ∗∗ [ww]
Power efficiency in terms of heat produced (%)	50 ∗ [xx]	65 ∗∗∗ [yy]	99 ∗ [zz]

Source: Own representation

[dd] Given a well-designed thermal management system and the reliability ECs estimated in table 11, all NETs should provide high versatility in line with a diesel engine "running full power in all conditions all the time" (G. Pope, personal communication, 04/01/2022). With MIM and FCO cells being the highest, followed by graphene harvester (lower power).

[ee] Coverage index (0.9) for semiconductor devices is high as sensor integration into individual microstructures within a wafer layer is quite feasible (Niklaus et al. 2012). Bandwidth index (0.9) is also high as I2C, or SPI (circuit board level protocols) are orders of magnitude higher than CAN bus: 0.9 x 0.9 = 0.81

[ff] Relative to a diesel engine, coverage index for FCO cells would be slightly better; on par with a battery array (0.85) (M. Reid, personal communication, 6/24/2022). Due to higher energy density, distance reduction between cells results in ability to use faster communication protocols (0.7). 0.85 x 0.7 = 0.6

[gg] Graphene device potentially follows more common physics models with conventional thermal fluctuation harvesting (Thibado et al. 2020). Mechanical and electrical engineers can transfer knowledge better.

[hh] MIM device relies on more advanced quantum theories (Moddel et al. 2021). Significantly less knowledge transfer for designers; however, conventional semiconductor package transfers some familiarity.

[ii] Physics and material science is highly complex resulting in very low knowledge transfer (M. Reid, personal communication, 2/1/2022).

[jj] ~50 sub-system parts constitute a robotic arm power system. Without solar cell sub-systems, part count could be cut to ~35 (A. Vargas, personal communication, 6/10/2022). Lower power density of the graphene device may require additional power modules relative to MIM device.

[kk] Similarities to battery cell modules without solar (M. Reid, personal communication, 6/24/2022).

[ll] Here, an electric motor would need to be considered as part of the power system replacing the diesel engine of a combine harvester which would increase the use of advanced materials slightly. Both semiconductor devices use sufficiently advanced non-combustible materials to operate (Moddel 2022; Thibado 2022).

[mm] Along with the reasoning in *ll*, most of the FCO cell mass requires very advanced materials (M. Reid, personal communication, 2/1/2022).

[nn] In the case of robotic arm power system, one less power bus is required due to elimination of solar panels for NETs (A. Vargas, personal communication, 6/10/2022).

[oo] Modularity and architectural flexibility enabled by the high-power density of a MIM device can improve options for robotic serviceability. Also, for a graphene device but slightly less due to lower power density.

[pp] Some uncertainties here, but in general FCO robotic serviceability would likely be on par with lithium batteries (M. Reid, personal communication, 6/24/2022).

[qq] As these semiconductor devices are a new category of technologies + the design cadence is generally slow (~3months), probabilities of reaching high TRL within the time horizons defined are moderate. See: https://www.nasa.gov/directorates/heo/scan/ engineering/technology/technology_readiness_level (retrieved on 6/16/2022)

[rr] Refer to *kk*, this battery analogy improves probability of achieving higher TRL levels quicker + faster design cadence (2-6weeks) (M. Reid, personal communication, 6/24/2022).

[ss] Based off interviews and online presentations + proof of application concepts still to be completed. (M. Reid, L. Lausin, personal communication, 6/24/2022). See: https://www.nasa.gov/directorates/heo/scan/ engineering/technology/technology_readiness_level (retrieved on 6/16/2022)

[tt] Redundancy is inherent to these NETs due to their matrix array structure and high energy densities (Thibado and Kumar 2017; Moddel 2020; M. Reid, personal communication, 6/24/2022).

[uu] Typical 5x5 QFN package has mass decomposition of < 0.5 % magnetizable material: http://www.irf.com/ehs/compliance/cr-qfn_5x5.pdf (retrieved on 6/16/2022). FCO cells are mostly non-magnetic as well (M. Reid, L. Lausin, personal communication, 6/24/2022).

[vv] No high-risk/hazardous materials currently present in NETs that are not already used in space (M. Reid, L. Lausin, personal communication, 6/24/2022).

[ww] Ability to modularize the semiconductor devices is apparent by the small QFN package form factors. The FCO cells are larger so modularity would be on par with battery arrays (M. Reid, personal communication, 6/24/2022).

[xx] Experimental results (Thibado 2022).

[yy] Efficiency is variable based on cell design and I^2R losses (Moddel 2020). 50% to 80% estimate.

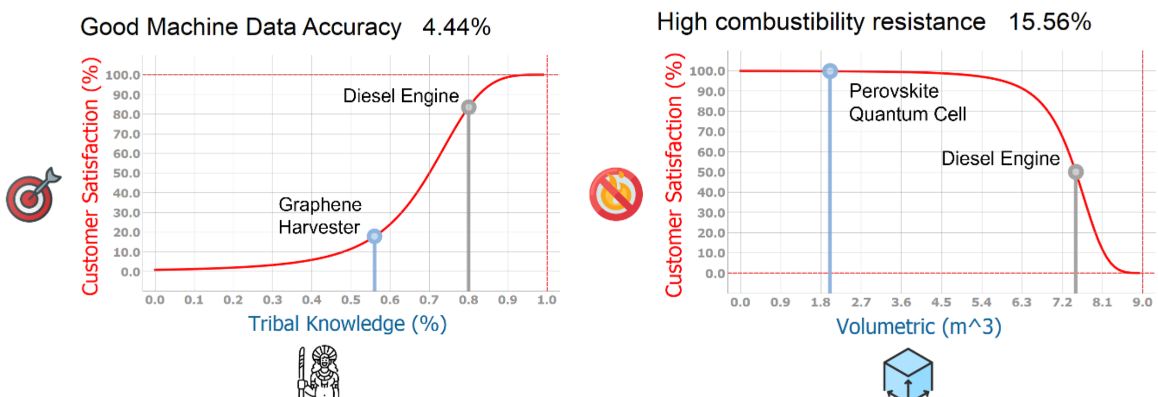
[zz] Device is very efficient, on par with lithium batteries (M. Reid, personal communication, 6/24/2022).

It's worth noting that ECs such as external RF shielding, safety system, and thermal system weights are not shown in table 12 due to their application dependency. During CODA, these characteristics are adjusted such that if power system weight can be reduced, then more weight can be added to external systems, or vice versa, described further in Appendix 8.3.

4.2.4 ODM Scoring

Copying over the merit curves from the baseline technologies, the EC estimates for each novel technology are applied to the merit functions[19] as illustrated below.

Figure 32: Example merit curves for combine harvester power system



Source: Own representation

[19] All ECs were estimated first before entering the values into the CODA matrices. This ensures less bias towards EC projections that could otherwise be influenced from observing ODM outputs.

Table 13 shows the resulting ODM scores. Exact EC estimates are available in Appendix 8.3.

Table 13: Novel technologies ODM scores

Novel Technology	CubeSat Power System #1	CubeSat Power System #2	Robotic Arm Power System	Combine Harvester Power System	Emergency Helicopter Power System
Graphene Harvester	70.50%	67.90%	77.00%	80.10%	76.10%
MIM + Optical Casimir Cavity	65.50%	68.30%	77.50%	84.60%	85.60%
Ferroelectric Oscillator	66.80%	73.50%	80.20%	85.10%	88.20%

Source: Own representation

4.3 ODM Benchmarking

The differences between baseline ODMs and novel ODMs are depicted below in table 14. These benchmark scores are positive when the novel technology has higher ODM than the baseline.

Table 14: Novel technologies ODM benchmark scores

Novel Technology	CubeSat Power System #1	CubeSat Power System #2	Robotic Arm Power System	Combine Harvester Power System	Emergency Helicopter Power System
Graphene Harvester	-10.00%	-10.30%	-6.40%	12.50%	-3.50%
MIM + Optical Casimir Cavity	-15.00%	-9.90%	-5.90%	17.00%	6.00%
Ferroelectric Oscillator	-13.70%	-4.70%	-3.20%	17.50%	8.60%

Source: Own representation

5 Discussion

The combined systematic perspectives and QFD methods performed in this paper support broad inferences to the research question:

> Given a selection of market sectors and applications, to what extent do novel energy technologies satisfy customer needs when contrasted to existing technologies?

Addressing the first part of the question, Section 3.2 referenced key aspects of ETIS, identifying market sectors and thereby establishing a set of baseline technologies that from an economic standpoint enable long term novel innovation viability. Correspondingly in 3.3, identification of three legitimate NETs were discovered through credibility metrics informed by lead-user interviews. Next, CN satisfaction for existing technologies was measured by interviews with industry experts, executing a CODA process, and defining CN-EC merit curve relationships resulting in five baseline ODM scores. Finally, EC estimates for NETs were developed and benchmarked against baseline ODMs, unveiling interesting CN relations between novel and baseline technologies, discussed further in the proceeding sections.

5.1 Interpretations

Table 15: Baseline and novel technology ODM matrix

Application	CubeSat Power System #1	CubeSat Power System #2	Robotic Arm Power System	Combine Harvester Power System	Emergency Helicopter Power System
Baseline Technology	Solar + Lithium Ion Battery	Solar + Lithium Ion Battery	Solar + Lithium Ion Battery	Diesel Engine	Lithium Polymer Battery
Baseline ODM	**80.50%**	**78.20%**	**83.40%**	**67.60%**	**79.60%**
Graphene Harvester	70.50%	67.90%	77.00%	80.10%	76.10%
MIM + Optical Casimir Cavity	65.50%	68.30%	77.50%	84.60%	85.60%
Ferroelectric Oscillator	66.80%	73.50%	80.20%	85.10%	88.20%

Source: Own representation

5.1.1 ODM Comparisons

Other than the combine harvester diesel engine, ODM scores for solar and lithium battery technologies showed consistently > 78% (table 15). A trend unsurprising due to the dense power delivery mechanisms a battery system offers relative to conventional fuel-based power systems. However, in the case of a combine harvester, simply replacing a diesel engine with an electric drivetrain and battery bank would be highly infeasible. Weight and volume limitations would be exceeded given the run time requirement of > 12hrs (G. Pope, personal communication, 2/18/2022). NETs overcome these limitations due to the versatile power-on-demand ZPE harvesting as seen by high ODM scores for the combine harvester in table 15.

Here, primary ECs driving these high scores are the zeroed-out values for *average consumable fuel input* as well as low *volumetric* requirements for NETs relative to a diesel engine.

In the emergency helicopter power system, NETs were closer to on par with lithium polymer battery technology. The ferroelectric crystal oscillator stood out with a 8.6% higher ODM driven by a maxed-out *energy density* (NETs have an infinite Watt hour per kg rating). The weight savings associated with power-on-demand generation allow more safety, thermal, and radiation shielding weight to be added, contributing to superior overall safety of the product.

For the robotic arm power system, overall NET merits were inferior to solar + lithium-ion batteries mainly due to lower *probabilities of achieving >= 8 TRL after 3 and 6 years*. Even so, noteworthy advantages were seen in terms of *power system weight*, *mechanical complexity*, *number of power bus lines*, and *robotically serviceable mass*. Elimination of solar panel sub-systems through NETs facilitate reduced part count, and weight savings, allowing increased buffer for design complexity around redundancy and serviceability.

Significantly lower ODM benchmark scores were observed for NETs when evaluating the CubeSat applications. *Inefficiencies in power* production cause excess heating, with small volumetric and weight constraints limiting thermal management solutions, potentially leading to integration challenges. Furthermore, while the NETs have good *modularity* and no *hazardous materials*, these gains were insufficient to counteract lacking *knowledge re-use* and low *sub-component TRL*; EC values that ultimately hinder design process efficiencies.

5.1.2 Emerging Design Characteristics

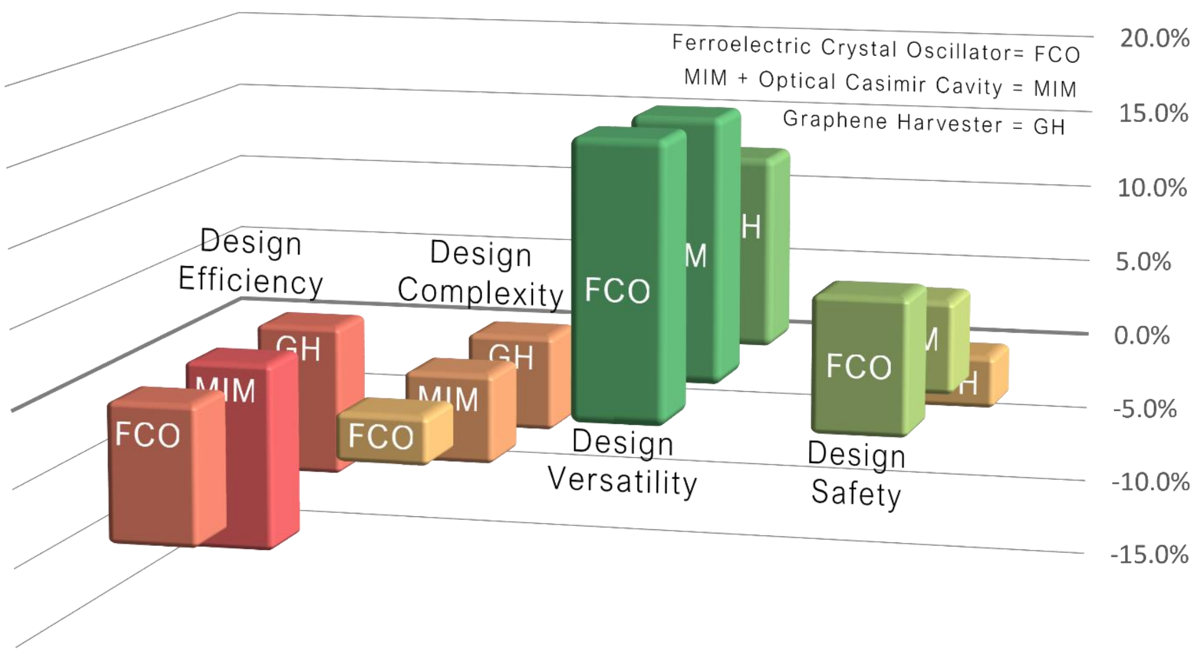
Hinted at in the previous and in Section 4.1, several design characteristics start to emerge after analyzing experts CN and EC preferences. For both CubeSat applications, dominant ODM drivers were CN-EC relationships that stressed a fast development program through *easy integration*, *technology readiness + certification*, and *knowledge reuse*. The robotic arm power system carried over some of these traits but with more emphasis given to system complexity that enables longer operational life. In the combine harvester application, versatility relationships drove higher ODM and in the emergency helicopter system this was safety.

By combining the CubeSat applications into one, 4 design characteristics can be defined and analyzed:

- Design Efficiency (CubeSats combined average).
- Design Complexity (robotic arm)
- Design Versatility (combine harvester)
- Design Safety (helicopter)

Separated by novel technology, table 14 is visualized by design characteristics below.

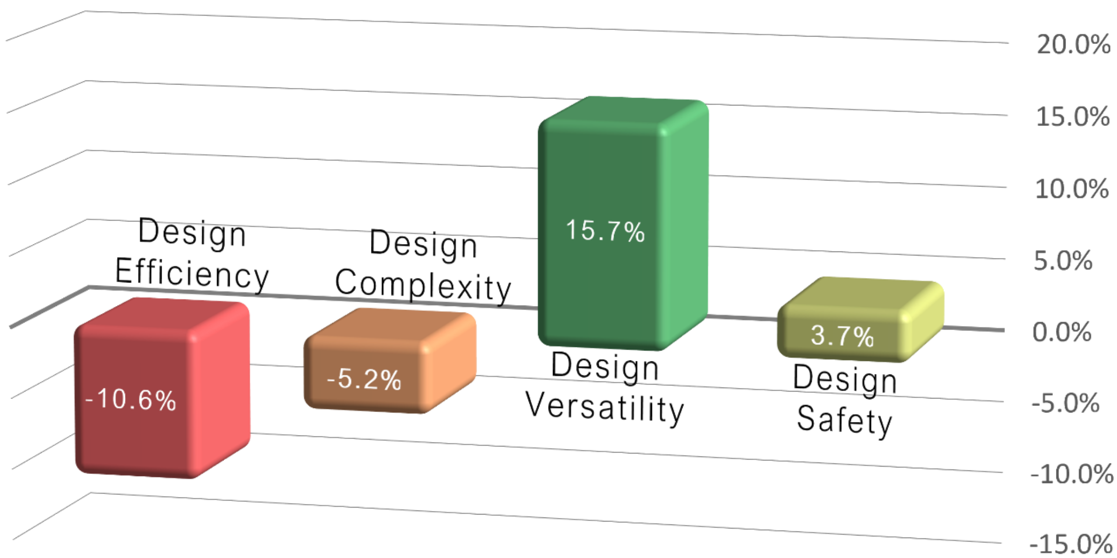
Figure 33: Design characteristics for each NET relative to existing solutions



Source: Own representation

Taking a column by column averaging of the previous figure, a high-level design characteristic picture of NETs can be constructed in figure 34.

Figure 34: Average design characteristics for NETs relative to existing solutions



Source: Own representation

5.2 Implications

Since ODM scores are directly associated with customer satisfaction, the patterns of ODM benchmarks illustrated in figures 33 & 34 answer this papers research question.

5.2.1 Customer Satisfaction

Categorized as design characteristics, NETs are extremely versatile with positive benefit towards safety and in some instances complexity. Therefore, taking all technology applications analyzed in this paper, the extent in which novel renewable energy technologies satisfy customer needs are in applications that benefit from these design characteristic distributions.

Customers will be extremely satisfied if their products require a very versatile power system, capable of handling dynamic load conditions for extended periods and in relatively harsh environments. If safety is also a design requirement, NETs can be comparable or better than current battery technologies. The power density and modularity of NETs can also, in some cases, assist in designs that require complex systems. That said, relative to existing technologies, NETs suffer from low design efficiency. Their current early research phases contribute to low technology readiness. Customers who require a technology that is fast to market with low engineering resources would not be satisfied in this respect.

5.2.2 Future Proliferation

With the aim of this study to bring awareness to the extraordinary energy research currently taking place; through this report, actors and institutions now have the opportunity to contemplate support for breakthrough innovation in the energy space. Connecting with advocacy groups, governments and private firms can assuredly invest in legitimate entrepreneurs and ensure appropriate markets sectors and applications are targeted. This fosters increasing R&D and knowledge spillover, leading to new technology standards and better economies of scale and scope. From a packaging and architecture standpoint all NETs discussed are fundamentally less complex and more modular than their counterparts. Over time, reliability and design efficiency characteristics are likely to improve, pioneering large scale adoption in everyday devices and in most market sectors.

5.3 Limitations

5.3.1 EC Estimations

It should be emphasized that none of the NETs analyzed in this paper have yet to demonstrate the projected power densities. The EC estimations were based on early experimental results, lead-user expert opinions, and comparable direct and indirect literature sources. The opinions and sources were reasonably formulated based on the current state of existing technologies; however, a moderate amount of risk exists in over or underestimating the ECs. Further R&D, experimentation, and manufacturing advancements would be required to limit estimation errors. Nevertheless, the ODM comparisons conducted here forecast encouraging potential in applications involving high versatility, safety, and in some instances complexity.

5.3.2 CODA Accuracy

The accuracy of CODA is summarized by three qualities: quantity of time/effort, number of knowledgeable experts, and scope of design. Typically, CODA works best through multi-day collaborative exercises with appropriate expert stakeholders (Eres et al. 2014, p. 83); an approach not feasible during the course of this thesis. However, with knowledgeable industry expert selections and a semi-automated CODA tool, time constraints could be counteracted, and data-entry visualizations improved conceptual decision making on the part of the experts during conducted interviews. With design scope, issues arise when the system under evaluation is too large and with too many interdependencies. ECs that contain too many features of the design (i.e., *power system weight*) become ambiguous and can result in situations where a design improvement reduces ODM. In the 5 baseline CODAs, this was present in some instances, but not widespread. Further follow up interviews could have addressed some of these inaccuracies by disambiguating/increasing the number of ECs. Lastly, during ODM benchmarking, without context for NETs, industry experts limited their potential customer satisfaction by the EC ranges chosen. The loss being unrealized customer satisfaction through orders of magnitude in improvements relative to existing technologies.

5.4 Recommendations

CODA is a practical tool for benchmarking multiple technologies within an application. Furthermore, interesting design characteristics that emerge during analysis of CN-EC relationships can summarize a technologies high-level properties. From this perspective, additional research into discovering different applications design characteristics could be explored to further understand the capabilities and limitations of NETs. CN merit data generated from this research could also be further analyzed by combining all CODA application data and categorizing by CNs (Safety CNs, Reliability CNs, Power CNs, etc.).

6 Conclusion

6.1 The Proliferation of Novel Energy Technologies

Three primary topics were analyzed in this report. Novel ZPE technologies, the energy innovation system (ETIS), and quality function deployment (QFD) methodologies; connecting all three through philosophic and techno-economic perspectives that combined, highlight potential paths towards commercialization and disruption in the renewable energy technology sector.

With novel technologies, their capabilities to harvest power in three dimensions unlock new and hybrid solutions that over time can solve critical infrastructure problems around electric grid balance and stability. Scaling these technologies require innovation strategies that encourage knowledge networks, standardization/vertical integration plans, and sustained investments from external actors and institutions. Focused effort in niche applications that are compatible with the design characteristics unveiled in this report will increase customer satisfaction relative to existing technologies and further encourage investors.

Enveloped by a philosophical perspective, deployment of these strategies requires awareness and open-mindedness. Technological revolutions rarely emerge from normal science but rather extraordinary research. Shifting resource/research allocations to these investigations is in fact not wasteful but is a critical part of the paradigmatic cycle predicted and evidenced by Thomas Kuhn.

6.2 A Note on Incommensurability

As highlighted in the introduction of this paper, the two phases of scientific progression, the normal and extraordinary, are not just different speeds of science, but fundamentally different approaches to scientific work (Waller 2020). This dichotomy of scientific method often leads to disagreement between the two practicing groups. Subsequent novel discoveries from extraordinary research may necessitate the need for a new paradigm, which further escalates criticisms from traditional practitioners. Kuhn describes this disagreement as resulting from the incommensurability of two competing paradigms (1970, p. 160). They observe differences about foundational questions such "as the existence of subatomic particles, the materiality of light, and the conservation of heat or of energy (..) [these] are the substantive differences between successive paradigms" (1970, p. 115). Kuhn cites multiple instances illustrating the outcomes of incommensurability; "X-rays, however, were greeted not only with surprise but with shock. Lord Kelvin at first pronounced them an elaborate hoax" (1970, p. 71) or "[t]he laymen who scoffed at Einstein's general theory of relativity because space could not be "curved"—it was not that sort of thing" (1970, p. 161). "Consider, for another example, the men who called Copernicus mad because he proclaimed that the earth moved" (1970, p. 161), even Darwin understood this concept of incommensurability in his writings; "Although I am fully convinced of the truth of the views given in this volume …, I by no means expect to convince experienced naturalists whose minds are stocked with a multitude of facts all viewed, during a long course of years, from a point of view directly opposite to mine. . . ." (Darwin 1889, as cited by Kuhn 1970, p. 163).

Now recall from 1.2, the experience of Victorian-era scientists confronted with the photovoltaic effect. When viewed from Kuhn's perspective it is apparent how the incompatibility of their wave optics paradigm[20] created challenges legitimizing the technology. Perhaps the extraordinary energy research happening today is not in a dissimilar situation… In hindsight, it is easy to critique the traditional paradigm and those that adhered to it, but during transitional periods from normal to extraordinary science it is often the brave researchers willing to explore anomalies, without hindsight, who realize the flaws and solve the 'puzzle' in a different way, that ultimately change the perspective and lead a paradigm shift for society.

20 For more details on the wave theory of light and how it failed to explain the Compton effect, photo-electric effect, light spectrum and others see: ikchris 2018 Optics #3:The Dual Nature of Light

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Signature

8 Appendix

8.1 BWM Figures

Appendix 1: Binary weight matrix for CubeSat power system #1

Cube Satellite Power System	Must be lightweight	Ease of integration testing	Should be highly efficient	Needs to have a medium lifetime (finish mission)	Must have good radiation resilience	Heritage (knowledge reuse)	x - scores	y - scores	total score	Biased Score	Normalized Score
Must be lightweight		1	0	1	0	0	2	0	2	3	14.3%
Ease of integration testing			1	0	0	0	1	0	1	2	9.5%
Should be highly efficient				0	0	0	0	1	1	2	9.5%
Needs to have a medium lifetime (finish mission)					1	1	2	2	4	5	23.8%
Must have good radiation resilience						0	0	3	3	4	19.0%
Heritage (knowledge reuse)							0	4	4	5	23.8%
	0	0	1	2	3	4	5	10	15	21	100.0%

Source: Q. Mannes, personal communication, 2/9/2022 (based on Eres et al. (2014))

Appendix 2: Binary weight matrix for CubeSat power system #2

Cube Satellite Power System #2	Must be Lightweight	Good Operating Life	Good Power Profile Over Orbit	Easy to Certify	Low Earth Magnetic Field Influence	Should have high TRL	x - scores	y - scores	total score	Biased Score	Normalized Score
Must be Lightweight		1	0	1	0	1	3	0	3	4	19.0%
Good Operating Life			1	1	1	1	4	0	4	5	23.8%
Good Power Profile Over Orbit				1	1	1	3	1	4	5	23.8%
Easy to Certify					0	0	0	0	0	1	4.8%
Low Earth Magnetic Field Influence						1	1	2	3	4	19.0%
Should have high TRL							0	1	1	2	9.5%
	0	0	1	0	2	1	11	4	15	21	100.0%

Source: J. Aerts, personal communication, 3/29/2022 (based on Eres et al. (2014))

Appendix 3: Binary weight matrix for Robotic Arm power system

Robotic Arm Power System	Must Meet Weight Requirements	Long Operating Life	Excellent Thermal Survivability	High Versatility (Varying Load Conditions)	Must Meet Volumetric Requirements	High Redundancy (Multiple Independent Systems)	High Serviceability	High Technology Readiness Level	x - scores	y - scores	total score	Biased Score	Normalized Score
Must Meet Weight Requirements		1	1	1	1	0	1	1	6	0	6	7	19.4%
Long Operating Life			0	0	0	0	1	1	2	0	2	3	8.3%
Excellent Thermal Survivability				1	1	0	0	1	3	1	4	5	13.9%
High Versatility (Varying Load Conditions)					0	0	0	1	1	1	2	3	8.3%
Must Meet Volumetric Requirements						0	0	0	0	2	2	3	8.3%
High Redundancy (Multiple Independent Systems)							1	1	2	5	7	8	22.2%
High Serviceability								0	0	3	3	4	11.1%
High Technology Readiness Level									0	2	2	3	8.3%
	0	0	1	1	2	5	3	2	14	14	28	36	100.0%

Source: A. Vargas, personal communication, 4/15/2022 (based on Eres et al. (2014))

Appendix 4: Binary weight matrix for Combine Harvester power system

Combine Harvester Power System	High Versatility	High Reliability	High Fuel Efficiency	Good Machine Data Accuracy	High Temp High Altitude Efficiency	High combustibility resistance	Should have easy Maintenance	Must meet Volumetric requirements	Must meet required Energy Balance	x - scores	y - scores	total score	Biased Score	Normalized Score
High Versatility		1	1	1	1	1	1	0	0	6	0	6	7	15.6%
High Reliability			1	1	1	1	1	0	0	5	0	5	6	13.3%
High Fuel Efficiency				1	1	0	1	0	0	3	0	3	4	8.9%
Good Machine Data Accuracy					0	0	1	0	0	1	0	1	2	4.4%
High Temp High Altitude Efficiency						0	0	0	0	0	1	1	2	4.4%
High combustibility resistance							1	1	1	3	3	6	7	15.6%
Should have easy Maintenance								0	0	0	1	1	2	4.4%
Must meet Volumetric requirements									1	1	6	7	8	17.8%
Must meet required Energy Balance										0	6	6	7	15.6%
	0	0	0	0	1	3	1	6	6	19	17	36	45	100.0%

Source: G. Pope, personal communication, 2/18/2022 (based on Eres et al. (2014))

Appendix 5: Binary weight matrix for Emergency Helicopter power system

Emergency Helicopter Powertrain System	Good Med/High Energy Content	High Power	High Safety	High One-Time Use Reliability	Long Shelf Life	Very low operating temperature	Good Vibration Resistance	High Altitude Operation	High Shock Resistance/Survivability	Good External Radiation Protection	Water and Particle ingress protections	x - scores	y - scores	total score	Biased Score	Normalized Score
Good Med/High Energy Content		0	0	0	1	1	0	0	1	1	1	5	0	5	6	9.1%
High Power			1	1	1	1	0	0	1	1	1	7	1	8	9	13.6%
High Safety				1	1	1	1	1	1	1	1	8	1	9	10	15.2%
High One-Time Use Reliability					1	1	1	1	1	1	1	7	1	8	9	13.6%
Long Shelf Life						1	1	1	0	0	0	3	0	3	4	6.1%
Very low operating temperature							0	1	1	1	1	4	0	4	5	7.6%
Good Vibration Resistance								1	1	1	1	4	3	7	8	12.1%
High Altitude Operation									0	0	1	1	2	3	4	6.1%
High Shock Resistance/Survivability										1	1	2	2	4	5	7.6%
Good External Radiation Protection											1	1	2	3	4	6.1%
Water and Particle ingress protections												0	1	1	2	3.0%
	0	1	1	1	0	0	3	2	2	2	1	42	13	55	66	100.0%

Source: T. Kahnert, personal communication, 2/8/2022 (based on Eres et al. (2014))

8.2 Baseline CODA Figures

Appendix 6: CODA matrix for CubeSat power system #1

Solar + Lithium-ion Batteries			Overall Design Merit (ODM): 80.5%	Must be lightweight	Ease of integration testing	Should be highly efficient	Needs to have a medium lifetime (finish mission)	Must have good radiation resilience	Heritage (knowledge reuse)
			Normalized Weights	14%	10%	10%	24%	19%	24%
Engineering Characteristics (EC's)									
Power System Weight (kg)			Correlation	0.9	0.1				
	Value	**2.50**	Function Type	Opt	Avoid				
	Lower Limit	0.00	Neutral or Optimum Point	0.00	8.00				
	Upper Limit	4.00	Tolerance	3.30	3.81				
			Power	4.00	8.00				
			Merit Value	75.2%	95.0%				
Radiation Shielding Weight (kg)			Correlation	0.3			0.3	0.9	
	Value	**0.20**	Function Type	Opt			Max	Opt	
	Lower Limit	0.00	Neutral or Optimum Point	0.00			0.09	0.20	
	Upper Limit	1.00	Tolerance	0.40				0.20	
			Power	2.00			2.00	2.00	
			Merit Value	80.0%			80.1%	100.0%	
Power Efficiency (%)			Correlation	0.3		0.9			
	Value	**95.00**	Function Type	Opt		Opt			
	Lower Limit	0.00	Neutral or Optimum Point	100.00		110.00			
	Upper Limit	100.00	Tolerance	12.00		30.00			
			Power	2.00		4.00			
			Merit Value	85.2%		94.1%			
Knowledge Reuse (%)			Correlation	0.1	0.1	0.1	0.3	0.1	0.9
	Value	**50.00**	Function Type	Max	Max	Max	Avoid	Avoid	Max
	Lower Limit	0.00	Neutral or Optimum Point	25.00	36.00	50.00	0.00	0.00	25.00
	Upper Limit	100.00	Tolerance				50.00	41.60	
			Power	2.00	4.00	2.00	6.00	6.00	2.00
			Merit Value	75.0%	85.4%	50.0%	50.0%	75.1%	75.0%
Mission Completeness (%)			Correlation				0.9		
	Value	**95.00**	Function Type				Opt		
	Lower Limit	0.00	Neutral or Optimum Point				110.00		
	Upper Limit	100.00	Tolerance				20.00		
			Power				8.00		
			Merit Value				90.9%		
Modularity (%)			Correlation	0.1	0.9				0.3
	Value	**50.00**	Function Type	Opt	Opt				Opt
	Lower Limit	0.00	Neutral or Optimum Point	50.00	100.00				100.00
	Upper Limit	100.00	Tolerance	30.00	81.20				40.00
			Power	2.00	2.00				2.00
			Merit Value	100.0%	72.5%				39.0%

Source: Q. Mannes, personal communication, 3/22/2022 (based on Eres et al. (2014))

Appendix 7: CODA matrix for CubeSat power system #2

Solar + Lithium-ion Batteries		Overall Design Merit (ODM)	78.2%	Must be Lightweight	Good Operating Life	Good Power Profile Over Orbit	Easy to Certify	Low Earth Magnetic Field Influence	Should have high TRL
			Normalized Weights	19%	24%	24%	5%	19%	10%
Engineering Characteristics (EC's)									
Power System Weight (kg)			Correlation	0.9	0.1	0.3			
	Value	1.50	Function Type	Opt	Max	Opt			
	Lower Limit	0.00	Neutral or Optimum Point	0.00	1.00	1.50			
	Upper Limit	8.00	Tolerance	2.00		3.00			
			Power	6.00	4.00	2.00			
			Merit Value	84.9%	87.5%	100.0%			
Available Avg Power Output (W)			Correlation	0.3	0.3	0.9			
	Value	25.00	Function Type	Min	Min	Avoid			
	Lower Limit	0.00	Neutral or Optimum Point	200.00	200.00	0.00			
	Upper Limit	100.00	Tolerance			9.00			
			Power	2.00	2.00	0.95			
			Merit Value	99.6%	99.6%	72.5%			
Power Efficiency (%)			Correlation	0.3	0.1	0.9			
	Value	90.00	Function Type	Opt	Opt	Opt			
	Lower Limit	0.00	Neutral or Optimum Point	105.00	105.00	105.00			
	Upper Limit	100.00	Tolerance	23.00	23.00	23.00			
			Power	4.00	4.00	6.00			
			Merit Value	84.7%	84.7%	92.9%			
Net Magnetizable Material Mass as percentage of total weight (%)			Correlation	0.1	0.3	0.3		0.9	
	Value	5.00	Function Type	Opt	Opt	Opt		Opt	
	Lower Limit	0.00	Neutral or Optimum Point	0.00	0.00	0.00		0.00	
	Upper Limit	100.00	Tolerance	200.00	10.00	10.00		12.00	
			Power	2.00	2.00	2.00		1.30	
			Merit Value	99.9%	80.0%	80.0%		75.7%	
Life Expectancy (years)			Correlation	0.9	0.9	0.9			0.3
	Value	3.00	Function Type	Min	Max	Opt			Max
	Lower Limit	0.00	Neutral or Optimum Point	7.00	1.00	10.00			0.90
	Upper Limit	10.00	Tolerance			7.80			
			Power	2.00	2.10	8.00			2.00
			Merit Value	80.2%	89.2%	70.4%			90.1%
Average Sub-component TRL (TRL)			Correlation		0.9		0.3		0.9
	Value	7.00	Function Type		Opt		Opt		Opt
	Lower Limit	1.00	Neutral or Optimum Point		10.00		9.00		9.00
	Upper Limit	9.00	Tolerance		3.00		2.52		2.64
			Power		4.00		6.00		4.00
			Merit Value		50.0%		80.0%		75.2%
# of high risk materials (# of materials)			Correlation	0.3	0.1	0.1	0.9		0.1
	Value	1.00	Function Type	Avoid	Avoid	Avoid	Opt		Avoid
	Lower Limit	0.00	Neutral or Optimum Point	-2.00	-0.30	-0.30	-0.60		7.00
	Upper Limit	5.00	Tolerance	2.00	0.90	0.90	2.00		5.00
			Power	1.00	2.00	2.00	4.00		6.00
			Merit Value	60.0%	67.6%	67.6%	70.9%		74.9%

Appendix 8: CODA matrix for Robotic Arm power system

Solar Powered Lithium Battery & PCU

Overall Design Merit (ODM): **83.4%**

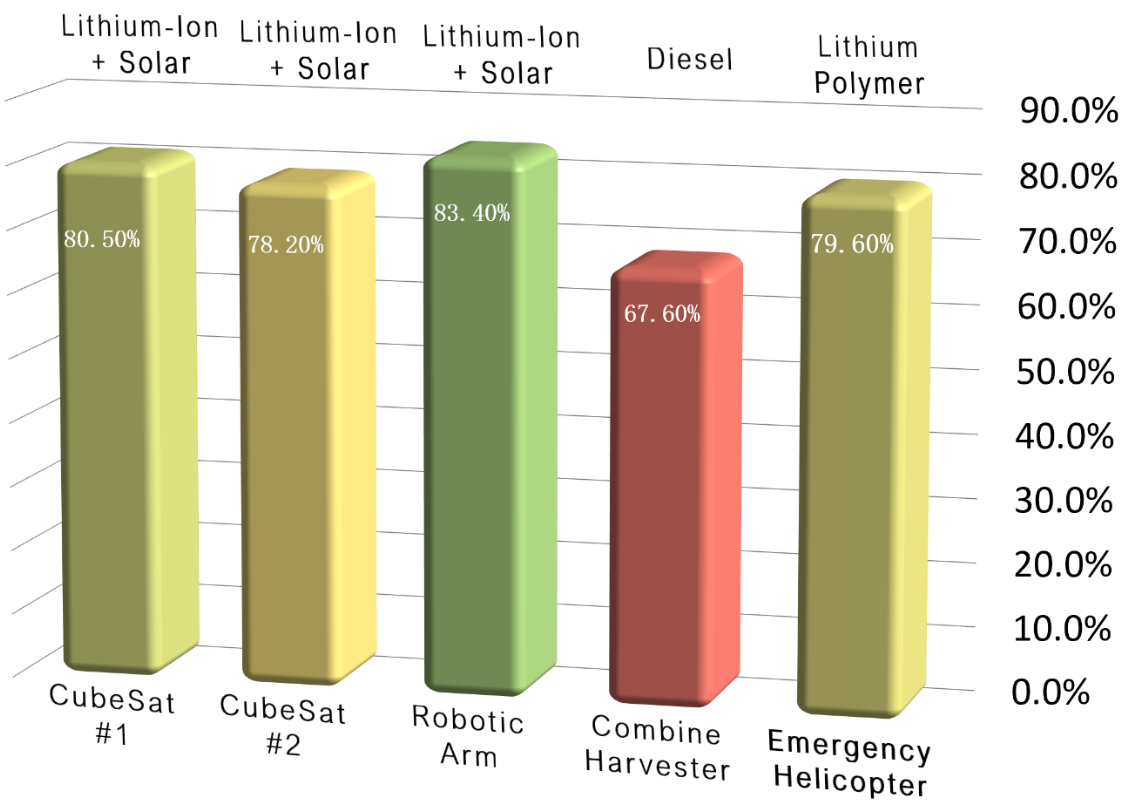
Engineering Characteristics (EC's)				Must Meet Weight Requirements	Long Operating Life	Excellent Thermal Survivability	High Versatility (Varying Load Conditions)	Must Meet Volumetric Requirements	High Redundancy (Multiple Independent Systems)	High Serviceability	High Technology Readiness Level
			Normalized Weights	19%	8%	14%	8%	8%	22%	11%	8%
Power System Weight (kg)			Correlation	0.9		0.1	0.3	0.3	0.9		
	Value	**350.00**	Function Type	Opt		Max	Max	Opt	Max		
	Lower Limit	50.00	Neutral or Optimum Point	0.00		300.00	300.00	0.00	130.00		
	Upper Limit	500.00	Tolerance	400.00				450.00			
			Power	8.00		4.00	4.00	6.00	2.00		
			Merit Value	74.4%		81.1%	81.1%	81.9%	92.6%		
Designing for Operating Life (years)			Correlation		0.9	0.9	0.1		0.9	0.3	0.9
	Value	**15.00**	Function Type		Max	Max	Max		Opt	Max	Max
	Lower Limit	8.00	Neutral or Optimum Point		10.00	10.00	10.00		20.00	10.00	8.50
	Upper Limit	20.00	Tolerance						6.00		
			Power		2.40	2.40	2.40		10.00	2.40	2.00
			Merit Value		95.3%	95.3%	95.3%		86.1%	95.3%	100.0%
Mechanical Complexity (# Parts)			Correlation	0.1	0.3				0.1	0.3	
	Value	**50.00**	Function Type	Opt	Opt				Opt	Opt	
	Lower Limit	20.00	Neutral or Optimum Point	0.00	0.00				30.00	45.00	
	Upper Limit	200.00	Tolerance	83.00	48.00				35.00	50.00	
			Power	4.50	9.00				2.00	2.00	
			Merit Value	90.7%	40.9%				75.4%	99.0%	
Temperature Delta while operating in -100 to 100 environment (delta C)			Correlation		0.3	0.9	0.1				0.1
	Value	**150.00**	Function Type		Avoid	Avoid	Avoid				Opt
	Lower Limit	90.00	Neutral or Optimum Point		90.00	90.00	90.00				200.00
	Upper Limit	200.00	Tolerance		20.00	20.00	31.00				100.00
			Power		2.00	2.70	3.00				4.00
			Merit Value		90.0%	95.1%	87.9%				94.1%
Number of Power Bus Lines (number of bus bars)			Correlation	0.3		0.1	0.9		0.3	0.1	
	Value	**5.00**	Function Type	Opt		Opt	Avoid		Avoid	Avoid	
	Lower Limit	2.00	Neutral or Optimum Point	3.00		4.00	0.00		0.00	10.00	
	Upper Limit	10.00	Tolerance	2.15		2.00	2.30		2.70	4.20	
			Power	3.00		2.00	4.00		6.00	8.00	
			Merit Value	55.4%		80.0%	95.7%		97.6%	80.1%	
Volume (m^3)			Correlation	0.3				0.9			
	Value	**3.38**	Function Type	Opt				Avoid			
	Lower Limit	0.03	Neutral or Optimum Point	0.00				12.00			
	Upper Limit	10.00	Tolerance	8.00				6.00			
			Power	2.00				6.00			
			Merit Value	84.9%				89.8%			
Robotically Servicable Mass (%)			Correlation	0.9	0.3			0.1	0.1	0.9	
	Value	**60.00**	Function Type	Min	Opt			Min	Opt	Opt	
	Lower Limit	0.00	Neutral or Optimum Point	100.00	100.00			100.00	125.00	125.00	
	Upper Limit	85.00	Tolerance		70.00				80.00	80.00	
			Power	1.50	2.00			2.00	2.00	2.00	
			Merit Value	49.1%	75.4%			68.5%	60.2%	60.2%	
Probability of achiving >= 8 TRL after 6 years (%)			Correlation	0.9	0.3	0.1	0.1	0.9	0.3		0.9
	Value	**95.00**	Function Type	Opt	Opt	Opt	Opt	Opt	Opt		Opt
	Lower Limit	0.00	Neutral or Optimum Point	100.00	100.00	100.00	100.00	100.00	100.00		100.00
	Upper Limit	100.00	Tolerance	30.00	21.00	21.00	40.00	30.00	40.00		21.00
			Power	1.50	1.50	1.50	1.50	1.50	1.50		1.50
			Merit Value	93.6%	89.6%	89.6%	95.8%	93.6%	95.8%		89.6%
Probability of achiving >= 8 TRL after 3 years (%)			Correlation	0.9	0.3	0.1	0.1	0.9	0.3		0.9
	Value	**75.00**	Function Type	Opt	Opt	Opt	Opt	Opt	Opt		Opt
	Lower Limit	0.00	Neutral or Optimum Point	100.00	100.00	100.00	100.00	100.00	100.00		100.00
	Upper Limit	100.00	Tolerance	40.00	38.00	38.00	45.00	40.00	45.00		38.00
			Power	2.00	2.00	2.00	2.00	2.00	2.00		2.00
			Merit Value	71.9%	69.8%	69.8%	76.4%	71.9%	76.4%		69.8%

Fault Tolerance Design (# faults that lead to catastrophic failure)			Correlation	0.1	0.3	0.3			0.9		0.3
	Value	2.00	Function Type	Opt	Avoid	Avoid			Avoid		Avoid
	Lower Limit	1.00	Neutral or Optimum Point	2.00	0.00	0.00			0.00		0.00
	Upper Limit	8.00	Tolerance	1.00	1.40	1.40			1.40		1.40
			Power	2.00	6.00	6.00			6.00		6.00
			Merit Value	100.0%	89.5%	89.5%			89.5%		89.5%

Power Output (W)			Correlation		0.1	0.3	0.9				
	Value	1750.00	Function Type		Opt	Opt	Opt				
	Lower Limit	200.00	Neutral or Optimum Point		200.00	200.00	2000.00				
	Upper Limit	10000.00	Tolerance		10000.00	10000.00	550.00				
			Power		1.00	1.00	2.00				
			Merit Value		86.6%	86.6%	82.9%				

Source: A. Vargas, personal communication, 6/7,10/2022 (based on Eres et al. (2014))

Appendix 9: From table 8 Baseline technology ODM scores



Source: Own representation

Appendix 10: CODA matrix for Combine Harvester power system

X911 Diesel Engine

Overall Design Merit (ODM) **67.6%**

Engineering Characteristics (EC's)				High Versatility	High Reliability	High Fuel Efficiency	Good Machine Data Accuracy	High Temp High Altitude Efficiency	High combustibility resistance	Should have easy Maintenance	Must meet Volumetric requirements	Must meet required Energy Balance
			Normalized Weights	16%	13%	9%	4%	4%	16%	4%	18%	16%
Weight Goals (kg)			Correlation	0.1	0.1						0.3	
	Value	**6000.00**	Function Type	Opt	Avoid						Min	
	Lower Limit	4000.00	Neutral or Optimum Point	4000.00	0.00						7000.00	
	Upper Limit	7000.00	Tolerance	2500.00	4160.00							
			Power	4.00	3.00						1.60	
			Merit Value	70.9%	75.0%						50.6%	
Versatility Index (idx)			Correlation	0.9	0.3	0.3	0.1	0.9	0.3	0.3	0.1	0.3
	Value	**0.85**	Function Type	Opt	Opt	Max	Max	Opt	Avoid	Max	Max	Max
	Lower Limit	0.00	Neutral or Optimum Point	1.00	1.00	0.25	0.50	1.00	0.00	0.25	0.20	0.30
	Upper Limit	1.00	Tolerance	0.30	0.26			0.20	0.70			
			Power	3.00	2.00	2.00	2.00	4.00	12.00	4.00	2.00	2.00
			Merit Value	88.9%	75.0%	90.5%	69.2%	76.0%	91.1%	99.1%	94.7%	86.0%
Power (KW)			Correlation	0.9	0.1	0.1		0.3				0.9
	Value	**455.00**	Function Type	Opt	Min	Opt		Min				Avoid
	Lower Limit	200.00	Neutral or Optimum Point	700.00	600.00	8000.00		800.00				0.00
	Upper Limit	700.00	Tolerance	348.00		15000.00						150.00
			Power	4.00	4.00	2.00		2.00				2.00
			Merit Value	80.3%	88.6%	79.8%		80.4%				90.2%
Altitude Rating (feet)			Correlation	0.3	0.1	0.3		0.9	0.1			
	Value	**4500.00**	Function Type	Max	Max	Opt		Opt	Opt			
	Lower Limit	0.00	Neutral or Optimum Point	1500.00	1500.00	7000.00		7000.00	7000.00			
	Upper Limit	7000.00	Tolerance			3000.00		3000.00	3000.00			
			Power	2.00	2.00	8.00		8.00	8.00			
			Merit Value	87.5%	87.5%	81.1%		81.1%	81.1%			
Avg Consumable Fuel Input (liters/hour)			Correlation	0.9		0.9		0.3	0.3			0.9
	Value	**89.00**	Function Type	Opt		Opt		Opt	Opt			Opt
	Lower Limit	0.00	Neutral or Optimum Point	0.00		0.00		0.00	0.00			0.00
	Upper Limit	200.00	Tolerance	80.00		80.00		80.00	80.00			126.00
			Power	4.00		4.00		4.00	4.00			4.00
			Merit Value	39.5%		39.5%		39.5%	39.5%			80.1%
Failure Rate (MTBF-hours)			Correlation	0.3	0.9		0.3	0.1	0.9	0.9		
	Value	**500.00**	Function Type	Avoid	Avoid		Avoid	Opt	Opt	Avoid		
	Lower Limit	0.00	Neutral or Optimum Point	0.00	0.00		0.00	2000.00	2000.00	0.00		
	Upper Limit	2000.00	Tolerance	460.00	460.00		250.00	1650.00	1000.00	350.00		
			Power	2.50	2.50		2.00	2.00	8.00	4.00		
			Merit Value	55.2%	55.2%		80.0%	54.8%	3.8%	80.6%		
Sensor Reporting Index (Coverage_Index*Bandwidth_Index)			Correlation	0.1	0.3	0.1	0.9	0.1	0.1	0.3		
	Value	**0.40**	Function Type	Max	Max	Max	Max	Max	Opt	Max		
	Lower Limit	0.00	Neutral or Optimum Point	0.50	0.50	0.50	0.50	0.50	1.00	0.50		
	Upper Limit	1.00	Tolerance						0.50			
			Power	6.00	6.00	6.00	6.00	6.00	6.00	6.00		
			Merit Value	76.2%	76.2%	76.2%	76.2%	76.2%	25.1%	76.2%		
Use of Advanced Materials (%)			Correlation	0.1	0.9	0.3		0.1	0.9	0.3	0.1	0.3
	Value	**0.50**	Function Type	Max	Max	Max		Max	Opt	Min	Max	Max
	Lower Limit	0.00	Neutral or Optimum Point	0.65	0.35	0.50		0.50	1.00	0.50	0.50	0.50
	Upper Limit	1.00	Tolerance						0.60			
			Power	6.00	5.00	5.00		5.00	2.00	2.00	4.00	5.00
			Merit Value	74.8%	90.0%	80.0%		80.0%	59.0%	50.0%	75.0%	80.0%
Tribal Knowledge (%)			Correlation	0.3	0.9	0.1	0.3	0.1	0.3	0.9	0.1	0.3
	Value	**0.80**	Function Type	Opt	Opt	Opt	Opt	Opt	Opt	Opt	Opt	Opt
	Lower Limit	0.00	Neutral or Optimum Point	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Upper Limit	1.00	Tolerance	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			Power	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
			Merit Value	83.5%	83.5%	83.5%	83.5%	83.5%	83.5%	83.5%	83.5%	83.5%
Volumetric (m^3)			Correlation						0.3	0.3	0.9	
	Value	**7.50**	Function Type						Avoid	Avoid	Avoid	
	Lower Limit	0.00	Neutral or Optimum Point						9.00	9.00	9.00	
	Upper Limit	9.00	Tolerance						1.50	1.50	1.50	
			Power						4.00	4.00	4.00	
			Merit Value						50.0%	50.0%	50.0%	

Source: G. Pope, personal communication, 4/1/2022 (based on Eres et al. (2014))

Appendix 11: CODA matrix for Emergency Helicopter power system

Lithium Polymer Battery		Overall Design Merit (ODM)	79.6%	Good Med/High Energy Content	High Power	High Safety	High One-Time Use Reliability	Long Shelf Life	Very low operating temperature	Good Vibration Resistance	High Altitude Operation	High Shock Resistance/Survivability	Good External Radiation Protection	Water and Particle ingress protections
			Normalized Weights	9%	14%	15%	14%	6%	8%	12%	6%	8%	6%	3%
Engineering Characteristics (EC's)														
Power System Weight (kg)			Correlation	0.9	0.9	0.9								
	Value	**80.00**	Function Type	Min	Opt	Opt								
	Lower Limit	0.00	Neutral or Optimum Point	266.00	0.00	0.00								
	Upper Limit	200.00	Tolerance		240.00	120.00								
			Power	2.00	2.00	2.00								
			Merit Value	90.0%	90.0%	69.2%								
RF Shielding Weight (kg)			Correlation										0.9	
	Value	**8.00**	Function Type										Opt	
	Lower Limit	0.00	Neutral or Optimum Point										16.00	
	Upper Limit	16.00	Tolerance										8.00	
			Power										2.00	
			Merit Value										50.0%	
Safety System Weight (kg)			Correlation			0.9								
	Value	**16.00**	Function Type			Opt								
	Lower Limit	0.00	Neutral or Optimum Point			25.00								
	Upper Limit	25.00	Tolerance			14.00								
			Power			2.00								
			Merit Value			70.8%								
Thermal System Weight (kg)			Correlation						0.9					
	Value	**16.00**	Function Type						Opt					
	Lower Limit	0.00	Neutral or Optimum Point						16.00					
	Upper Limit	32.00	Tolerance						14.00					
			Power						2.00					
			Merit Value						100.0%					
Specific Power Rating (W/kg)			Correlation	0.3	0.9	0.9								
	Value	**8000.00**	Function Type	Min	Opt	Opt								
	Lower Limit	0.00	Neutral or Optimum Point	11000.00	9000.00	8000.00								
	Upper Limit	10000.00	Tolerance		3000.00	3000.00								
			Power	2.00	2.00	2.00								
			Merit Value	61.4%	90.0%	100.0%								
Energy Density (Wh/kg)			Correlation	0.9	0.9	0.9								
	Value	**150.00**	Function Type	Opt	Max	Max								
	Lower Limit	0.00	Neutral or Optimum Point	300.00	65.00	90.00								
	Upper Limit	300.00	Tolerance	100.00										
			Power	2.00	2.00	2.00								
			Merit Value	30.8%	79.8%	68.5%								
Inches Per Sec Rating (IPS_rms)			Correlation			0.9	0.3			0.9				
	Value	**2.00**	Function Type			Opt	Max			Max				
	Lower Limit	0.00	Neutral or Optimum Point			2.50	0.30			0.30				
	Upper Limit	3.00	Tolerance			1.50								
			Power			2.00	2.00			2.00				
			Merit Value			90.0%	99.0%			99.0%				
Failure Rate (MTBF-hours)			Correlation	0.1	0.1	0.9	0.9		0.1	0.3	0.1	0.1	0.1	0.1
	Value	**100000.00**	Function Type	Max	Max	Max	Max		Max	Max	Max	Max	Max	Max
	Lower Limit	1000.00	Neutral or Optimum Point	30000.00	30000.00	37800.00	37800.00		18000.00	37800.00	37800.00	11600.00	37800.00	37800.00
	Upper Limit	150000.00	Tolerance											
			Power	2.00	2.00	2.00	2.00		2.00	2.00	2.00	2.00	2.00	2.00
			Merit Value	90.6%	90.1%	84.0%	84.0%		97.9%	84.0%	84.0%	99.7%	84.0%	84.0%
Expected Shelf Life (years)			Correlation	0.1		0.3	0.3	0.9						0.9
	Value	**10.00**	Function Type	Max		Max	Max	Opt						Max
	Lower Limit	0.00	Neutral or Optimum Point	5.00		4.30	4.30	12.00						3.70
	Upper Limit	15.00	Tolerance					6.00						
			Power	2.00		2.00	2.00	2.00						2.00
			Merit Value	75.0%		80.1%	80.1%	90.0%						84.6%
Component Rating Confidence (%)			Correlation			0.9	0.9	0.3	0.1	0.9	0.3	0.1		
	Value	**70.00**	Function Type			Opt	Opt	Opt	Opt	Opt	Opt	Opt		
	Lower Limit	0.00	Neutral or Optimum Point			100.00	100.00	100.00	100.00	100.00	100.00	100.00		
	Upper Limit	100.00	Tolerance			45.00	45.00	30.00	20.00	45.00	70.00	40.00		
			Power			2.00	2.00	2.00	2.00	2.00	2.00	2.00		
			Merit Value			69.2%	69.2%	50.0%	30.8%	69.2%	84.5%	64.0%		
Shock Rating (g's)			Correlation			0.3	0.1					0.9		
	Value	**30.00**	Function Type			Opt	Opt					Opt		
	Lower Limit	0.00	Neutral or Optimum Point			60.00	60.00					60.00		
	Upper Limit	60.00	Tolerance			70.00	70.00					70.00		
			Power			2.00	2.00					2.00		
			Merit Value			84.5%	84.5%					84.5%		
Rated Altitude (kPa)			Correlation			0.1					0.9			
	Value	**55.00**	Function Type			Opt					Opt			
	Lower Limit	50.00	Neutral or Optimum Point			50.00					50.00			
	Upper Limit	150.00	Tolerance			10.00					10.00			
			Power			2.00					2.00			
			Merit Value			80.0%					80.0%			

Source: T. Kahnert, personal communication, 3/9,15/2022 (based on Eres et al. (2014))

8.3 Novel Technology CODA Figures

Appendix 12: CODA matrix for CubeSat power system #1 (Graphene Harvester)

Graphene Harvester

Overall Design Merit (ODM): 70.5%

Engineering Characteristics (EC's)				Must be lightweight	Ease of integration testing	Should be highly efficient	Needs to have a medium lifetime (finish mission)	Must have good radiation resiliance	Heritage (knowledge reuse)
			Normalized Weights	14%	10%	10%	24%	19%	24%
Power System Weight (kg)			Correlation	0.9	0.1				
	Value	**1.80**	Function Type	Opt	Avoid				
	Lower Limit	0.00	Neutral or Optimum Point	0.00	8.00				
	Upper Limit	4.00	Tolerance	3.30	3.81				
			Power	4.00	8.00				
			Merit Value	91.9%	98.0%				
Radiation Shielding Weight (kg)			Correlation	0.3			0.3	0.9	
	Value	**0.20**	Function Type	Opt			Max	Opt	
	Lower Limit	0.00	Neutral or Optimum Point	0.00			0.09	0.20	
	Upper Limit	1.00	Tolerance	0.40				0.20	
			Power	2.00			2.00	2.00	
			Merit Value	80.0%			80.1%	100.0%	
Power Efficiency (%)			Correlation	0.3		0.9			
	Value	**50.00**	Function Type	Opt		Opt			
	Lower Limit	0.00	Neutral or Optimum Point	100.00		110.00			
	Upper Limit	100.00	Tolerance	12.00		30.00			
			Power	2.00		4.00			
			Merit Value	5.4%		5.9%			
Knowledge Reuse (%)			Correlation	0.1	0.1	0.1	0.3	0.1	0.9
	Value	**35.00**	Function Type	Max	Max	Max	Avoid	Avoid	Max
	Lower Limit	0.00	Neutral or Optimum Point	25.00	36.00	50.00	0.00	0.00	25.00
	Upper Limit	100.00	Tolerance				50.00	41.60	
			Power	2.00	4.00	2.00	6.00	6.00	2.00
			Merit Value	62.1%	74.0%	38.4%	10.5%	26.2%	62.1%
Mission Completeness (%)			Correlation				0.9		
	Value	**95.00**	Function Type				Opt		
	Lower Limit	0.00	Neutral or Optimum Point				110.00		
	Upper Limit	100.00	Tolerance				20.00		
			Power				8.00		
			Merit Value				90.9%		
Modularity (%)			Correlation	0.1	0.9				0.3
	Value	**80.00**	Function Type	Opt	Opt				Opt
	Lower Limit	0.00	Neutral or Optimum Point	50.00	100.00				100.00
	Upper Limit	100.00	Tolerance	30.00	81.20				40.00
			Power	2.00	2.00				2.00
			Merit Value	50.0%	94.3%				80.0%

Notes: Assuming system needs peak 100W, then graphene harvester would need to be 55W/kg x ~1.8kg

Appendix 13: CODA matrix for CubeSat power system #1 (MIM)

MIM + Optical Casimir Cavity

Engineering Characteristics (EC's)				Must be lightweight	Ease of integration testing	Should be highly efficient	Needs to have a medium lifetime (finish mission)	Must have good radiation resiliance	Heritage (knowledge reuse)
Overall Design Merit (ODM)		65.5%							
			Normalized Weights	14%	10%	10%	24%	19%	24%
Power System Weight (kg)			Correlation	0.9	0.1				
	Value	**0.10**	Function Type	Opt	Avoid				
	Lower Limit	0.00	Neutral or Optimum Point	0.00	8.00				
	Upper Limit	4.00	Tolerance	3.30	3.81				
			Power	4.00	8.00				
			Merit Value	100.0%	99.7%				
Radiation Shielding Weight (kg)			Correlation	0.3			0.3	0.9	
	Value	**0.20**	Function Type	Opt			Max	Opt	
	Lower Limit	0.00	Neutral or Optimum Point	0.00			0.09	0.20	
	Upper Limit	1.00	Tolerance	0.40				0.20	
			Power	2.00			2.00	2.00	
			Merit Value	80.0%			80.1%	100.0%	
Power Efficiency (%)			Correlation	0.3		0.9			
	Value	**65.00**	Function Type	Opt		Opt			
	Lower Limit	0.00	Neutral or Optimum Point	100.00		110.00			
	Upper Limit	100.00	Tolerance	12.00		30.00			
			Power	2.00		4.00			
			Merit Value	10.5%		16.5%			
Knowledge Reuse (%)			Correlation	0.1	0.1	0.1	0.3	0.1	0.9
	Value	**15.00**	Function Type	Max	Max	Max	Avoid	Avoid	Max
	Lower Limit	0.00	Neutral or Optimum Point	25.00	36.00	50.00	0.00	0.00	25.00
	Upper Limit	100.00	Tolerance				50.00	41.60	
			Power	2.00	4.00	2.00	6.00	6.00	2.00
			Merit Value	34.0%	43.9%	18.8%	0.1%	0.2%	34.0%
Mission Completeness (%)			Correlation				0.9		
	Value	**95.00**	Function Type				Opt		
	Lower Limit	0.00	Neutral or Optimum Point				110.00		
	Upper Limit	100.00	Tolerance				20.00		
			Power				8.00		
			Merit Value				90.9%		
Modularity (%)			Correlation	0.1	0.9				0.3
	Value	**80.00**	Function Type	Opt	Opt				Opt
	Lower Limit	0.00	Neutral or Optimum Point	50.00	100.00				100.00
	Upper Limit	100.00	Tolerance	30.00	81.20				40.00
			Power	2.00	2.00				2.00
			Merit Value	50.0%	94.3%				80.0%

Notes: Assuming system needs peak 100W, then MIM device would need to be 1071W/kg x ~0.1kg

Appendix 14: CODA matrix for CubeSat power system #1 (FCO)

Ferroelectric Crystal Oscillator

Overall Design Merit (ODM): 66.8%

Engineering Characteristics (EC's)				Must be lightweight	Ease of integration testing	Should be highly efficient	Needs to have a medium lifetime (finish mission)	Must have good radiation resiliance	Heritage (knowledge reuse)
			Normalized Weights	14%	10%	10%	24%	19%	24%
Power System Weight (kg)			Correlation	0.9	0.1				
	Value	**0.10**	Function Type	Opt	Avoid				
	Lower Limit	0.00	Neutral or Optimum Point	0.00	8.00				
	Upper Limit	4.00	Tolerance	3.30	3.81				
			Power	4.00	8.00				
			Merit Value	100.0%	99.7%				
Radiation Shielding Weight (kg)			Correlation	0.3			0.3	0.9	
	Value	**0.20**	Function Type	Opt			Max	Opt	
	Lower Limit	0.00	Neutral or Optimum Point	0.00			0.09	0.20	
	Upper Limit	1.00	Tolerance	0.40				0.20	
			Power	2.00			2.00	2.00	
			Merit Value	80.0%			80.1%	100.0%	
Power Efficiency (%)			Correlation	0.3		0.9			
	Value	**99.00**	Function Type	Opt		Opt			
	Lower Limit	0.00	Neutral or Optimum Point	100.00		110.00			
	Upper Limit	100.00	Tolerance	12.00		30.00			
			Power	2.00		4.00			
			Merit Value	99.3%		98.2%			
Knowledge Reuse (%)			Correlation	0.1	0.1	0.1	0.3	0.1	0.9
	Value	**5.00**	Function Type	Max	Max	Max	Avoid	Avoid	Max
	Lower Limit	0.00	Neutral or Optimum Point	25.00	36.00	50.00	0.00	0.00	25.00
	Upper Limit	100.00	Tolerance				50.00	41.60	
			Power	2.00	4.00	2.00	6.00	6.00	2.00
			Merit Value	12.9%	17.5%	6.7%	0.0%	0.0%	12.9%
Mission Completeness (%)			Correlation				0.9		
	Value	**95.00**	Function Type				Opt		
	Lower Limit	0.00	Neutral or Optimum Point				110.00		
	Upper Limit	100.00	Tolerance				20.00		
			Power				8.00		
			Merit Value				90.9%		
Modularity (%)			Correlation	0.1	0.9				0.3
	Value	**50.00**	Function Type	Opt	Opt				Opt
	Lower Limit	0.00	Neutral or Optimum Point	50.00	100.00				100.00
	Upper Limit	100.00	Tolerance	30.00	81.20				40.00
			Power	2.00	2.00				2.00
			Merit Value	100.0%	72.5%				39.0%

Notes: Assuming system needs peak 100W, then MIM device would need to be 1000W/kg x ~0.1kg

Appendix 15: CODA matrix for CubeSat power system #2 (Graphene Harvester)

Graphene Harvester				Must be Lightweight	Good Operating Life	Good Power Profile Over Orbit	Easy to Certify	Low Earth Magnetic Field Influence	Should have high TRL
		Overall Design Merit (ODM)	67.9%						
			Normalized Weights	19%	24%	24%	5%	19%	10%
Engineering Characteristics (EC's)									
Power System Weight (kg)			Correlation	0.9	0.1	0.3			
	Value	0.80	Function Type	Opt	Max	Opt			
	Lower Limit	0.00	Neutral or Optimum Point	0.00	1.00	1.50			
	Upper Limit	8.00	Tolerance	2.00		3.00			
			Power	6.00	4.00	2.00			
			Merit Value	99.6%	67.0%	94.8%			
Available Avg Power Output (W)			Correlation	0.3	0.3	0.9			
	Value	44.64	Function Type	Min	Min	Avoid			
	Lower Limit	0.00	Neutral or Optimum Point	200.00	200.00	0.00			
	Upper Limit	100.00	Tolerance			9.00			
			Power	2.00	2.00	0.95			
			Merit Value	95.5%	95.5%	82.1%			
Power Efficiency (%)			Correlation	0.3	0.1	0.9			
	Value	50.00	Function Type	Opt	Opt	Opt			
	Lower Limit	0.00	Neutral or Optimum Point	105.00	105.00	105.00			
	Upper Limit	100.00	Tolerance	23.00	23.00	23.00			
			Power	4.00	4.00	6.00			
			Merit Value	3.0%	3.0%	0.5%			
Net Magnetizable Material Mass as percentage of total weight (%)			Correlation	0.1	0.3	0.3		0.9	
	Value	0.50	Function Type	Opt	Opt	Opt		Opt	
	Lower Limit	0.00	Neutral or Optimum Point	0.00	0.00	0.00		0.00	
	Upper Limit	100.00	Tolerance	200.00	10.00	10.00		12.00	
			Power	2.00	2.00	2.00		1.30	
			Merit Value	100.0%	99.8%	99.8%		98.4%	
Life Expectancy (years)			Correlation	0.9	0.9	0.9			0.3
	Value	6.00	Function Type	Min	Max	Opt			Max
	Lower Limit	0.00	Neutral or Optimum Point	7.00	1.00	10.00			0.90
	Upper Limit	10.00	Tolerance			7.80			
			Power	2.00	2.00	8.00			2.00
			Merit Value	55.5%	98.4%	99.5%			99.0%
Average Sub-component TRL (TRL)			Correlation		0.9		0.3		0.9
	Value	2.00	Function Type		Opt		Opt		Opt
	Lower Limit	1.00	Neutral or Optimum Point		10.00		9.00		9.00
	Upper Limit	9.00	Tolerance		3.00		2.52		2.64
			Power		4.00		6.00		4.00
			Merit Value		1.9%		0.2%		2.0%
# of high risk materials (# of materials)			Correlation	0.3	0.1	0.1	0.9		0.1
	Value	0.00	Function Type	Avoid	Avoid	Avoid	Opt		Avoid
	Lower Limit	0.00	Neutral or Optimum Point	-2.00	-0.30	-0.30	-0.60		7.00
	Upper Limit	5.00	Tolerance	2.00	0.90	0.90	2.00		5.00
			Power	1.00	2.00	2.00	4.00		6.00
			Merit Value	50.0%	10.0%	10.0%	99.2%		88.3%

Notes: Optimal power to weight governed by 0.8kg x 55W/kg = 44W. Life expectancy limited to 6 years as this is optimal ODM.

Appendix 16: CODA matrix for CubeSat power system #2 (MIM)

MIM + Optical Casimir Cavity

				Must be Lightweight	Good Operating Life	Good Power Profile Over Orbit	Easy to Certify	Low Earth Magnetic Field Influence	Should have high TRL
		Overall Design Merit (ODM)	**68.3%**						
			Normalized Weights	19%	24%	24%	5%	19%	10%
Engineering Characteristics (EC's)									
Power System Weight (kg)			Correlation	0.9	0.1	0.3			
	Value	**0.80**	Function Type	Opt	Max	Opt			
	Lower Limit	0.00	Neutral or Optimum Point	0.00	1.00	1.50			
	Upper Limit	8.00	Tolerance	2.00		3.00			
			Power	6.00	4.00	2.00			
			Merit Value	99.6%	67.0%	94.8%			
Available Avg Power Output (W)			Correlation	0.3	0.3	0.9			
	Value	**65.00**	Function Type	Min	Min	Avoid			
	Lower Limit	0.00	Neutral or Optimum Point	200.00	200.00	0.00			
	Upper Limit	100.00	Tolerance			9.00			
			Power	2.00	2.00	0.95			
			Merit Value	88.1%	88.1%	86.7%			
Power Efficiency (%)			Correlation	0.3	0.1	0.9			
	Value	**65.00**	Function Type	Opt	Opt	Opt			
	Lower Limit	0.00	Neutral or Optimum Point	105.00	105.00	105.00			
	Upper Limit	100.00	Tolerance	23.00	23.00	23.00			
			Power	4.00	4.00	6.00			
			Merit Value	9.9%	9.9%	3.5%			
Net Magnetizable Material Mass as percentage of total weight (%)			Correlation	0.1	0.3	0.3		0.9	
	Value	**0.50**	Function Type	Opt	Opt	Opt		Opt	
	Lower Limit	0.00	Neutral or Optimum Point	0.00	0.00	0.00		0.00	
	Upper Limit	100.00	Tolerance	200.00	10.00	10.00		12.00	
			Power	2.00	2.00	2.00		1.30	
			Merit Value	100.0%	99.8%	99.8%		98.4%	
Life Expectancy (years)			Correlation	0.9	0.9	0.9			0.3
	Value	**6.00**	Function Type	Min	Max	Opt			Max
	Lower Limit	0.00	Neutral or Optimum Point	7.00	1.00	10.00			0.90
	Upper Limit	10.00	Tolerance			7.80			
			Power	2.00	2.00	8.00			2.00
			Merit Value	55.5%	98.4%	99.5%			99.0%
Average Sub-component TRL (TRL)			Correlation		0.9		0.3		0.9
	Value	**2.00**	Function Type		Opt		Opt		Opt
	Lower Limit	1.00	Neutral or Optimum Point		10.00		9.00		9.00
	Upper Limit	9.00	Tolerance		3.00		2.52		2.64
			Power		4.00		6.00		4.00
			Merit Value		1.9%		0.2%		2.0%
# of high risk materials (# of materials)			Correlation	0.3	0.1	0.1	0.9		0.1
	Value	**0.00**	Function Type	Avoid	Avoid	Avoid	Opt		Avoid
	Lower Limit	0.00	Neutral or Optimum Point	-2.00	-0.30	-0.30	-0.60		7.00
	Upper Limit	5.00	Tolerance	2.00	0.90	0.90	2.00		5.00
			Power	1.00	2.00	2.00	4.00		6.00
			Merit Value	50.0%	10.0%	10.0%	99.2%		88.3%

Notes: Optimal power to weight governed by 0.8kg x 1071W/kg = 857W which is >> 100W. 65W optimal power output based on existing merit curves. Life expectancy limited to 6 years as this is optimal ODM.

Appendix 17: CODA matrix for CubeSat power system #2 (FCO)

Ferroelectric Crystal Oscillator			Overall Design Merit (ODM): 73.5%	Must be Lightweight	Good Operating Life	Good Power Profile Over Orbit	Easy to Certify	Low Earth Magnetic Field Influence	Should have high TRL
			Normalized Weights	19%	24%	24%	5%	19%	10%
Engineering Characteristics (EC's)									
Power System Weight (kg)			Correlation	0.9	0.1	0.3			
	Value	**0.80**	Function Type	Opt	Max	Opt			
	Lower Limit	0.00	Neutral or Optimum Point	0.00	1.00	1.50			
	Upper Limit	8.00	Tolerance	2.00		3.00			
			Power	6.00	4.00	2.00			
			Merit Value	99.6%	67.0%	94.8%			
Available Avg Power Output (W)			Correlation	0.3	0.3	0.9			
	Value	**65.00**	Function Type	Min	Min	Avoid			
	Lower Limit	0.00	Neutral or Optimum Point	200.00	200.00	0.00			
	Upper Limit	100.00	Tolerance			9.00			
			Power	2.00	2.00	0.95			
			Merit Value	88.1%	88.1%	86.7%			
Power Efficiency (%)			Correlation	0.3	0.1	0.9			
	Value	**90.00**	Function Type	Opt	Opt	Opt			
	Lower Limit	0.00	Neutral or Optimum Point	105.00	105.00	105.00			
	Upper Limit	100.00	Tolerance	23.00	23.00	23.00			
			Power	4.00	4.00	6.00			
			Merit Value	84.7%	84.7%	92.9%			
Net Magnetizable Material Mass as percentage of total weight (%)			Correlation	0.1	0.3	0.3		0.9	
	Value	**3.00**	Function Type	Opt	Opt	Opt		Opt	
	Lower Limit	0.00	Neutral or Optimum Point	0.00	0.00	0.00		0.00	
	Upper Limit	100.00	Tolerance	200.00	10.00	10.00		12.00	
			Power	2.00	2.00	2.00		1.30	
			Merit Value	100.0%	91.7%	91.7%		85.8%	
Life Expectancy (years)			Correlation	0.9	0.9	0.9			0.3
	Value	**6.00**	Function Type	Min	Max	Opt			Max
	Lower Limit	0.00	Neutral or Optimum Point	7.00	1.00	10.00			0.90
	Upper Limit	10.00	Tolerance			7.80			
			Power	2.00	2.00	8.00			2.00
			Merit Value	55.5%	98.4%	99.5%			99.0%
Average Sub-component TRL (TRL)			Correlation		0.9		0.3		0.9
	Value	**3.00**	Function Type		Opt		Opt		Opt
	Lower Limit	1.00	Neutral or Optimum Point		10.00		9.00		9.00
	Upper Limit	9.00	Tolerance		3.00		2.52		2.64
			Power		4.00		6.00		4.00
			Merit Value		3.3%		0.5%		3.6%
# of high risk materials (# of materials)			Correlation	0.3	0.1	0.1	0.9		0.1
	Value	**0.00**	Function Type	Avoid	Avoid	Avoid	Opt		Avoid
	Lower Limit	0.00	Neutral or Optimum Point	-2.00	-0.30	-0.30	-0.60		7.00
	Upper Limit	5.00	Tolerance	2.00	0.90	0.90	2.00		5.00
			Power	1.00	2.00	2.00	4.00		6.00
			Merit Value	50.0%	10.0%	10.0%	99.2%		88.3%

Notes: Optimal power to weight governed by 0.8kg x 1000W/kg = 800W which is >> 100W. 65W optimal power output based on existing merit curves. Life expectancy limited to 6 years as this is optimal ODM.

Appendix 18: CODA matrix for Robotic Arm power system (Graphene Harvester)

Graphene Harvester		Overall Design Merit (ODM)	77.0%	Must Meet Weight Requirements	Long Operating Life	Excellent Thermal Survivability	High Versatility (Varying Load Conditions)	Must Meet Volumetric Requirements	High Redundancy (Multiple Independent Systems)	High Serviceability	High Technology Readiness Level
			Normalized Weights	19%	8%	14%	8%	8%	22%	11%	8%
Engineering Characteristics (EC's)											
Power System Weight (kg)			Correlation	0.9		0.1	0.3	0.3	0.9		
	Value	305.00	Function Type	Opt		Max	Max	Opt	Max		
	Lower Limit	50.00	Neutral or Optimum Point	0.00		300.00	300.00	0.00	130.00		
	Upper Limit	500.00	Tolerance	400.00				450.00			
			Power	8.00		4.00	4.00	6.00	2.00		
			Merit Value	89.7%		75.7%	75.7%	91.2%	89.0%		
Designing for Operating Life (years)			Correlation		0.9	0.9	0.1		0.9	0.3	0.9
	Value	15.00	Function Type		Max	Max	Max		Opt	Max	Max
	Lower Limit	8.00	Neutral or Optimum Point		10.00	10.00	10.00		20.00	10.00	8.50
	Upper Limit	20.00	Tolerance						6.00		
			Power		2.40	2.40	2.40		10.00	2.40	2.00
			Merit Value		95.3%	95.3%	95.3%		86.1%	95.3%	100.0%
Mechanical Complexity (# Parts)			Correlation	0.1	0.3				0.1	0.3	
	Value	40.00	Function Type	Opt	Opt				Opt	Opt	
	Lower Limit	20.00	Neutral or Optimum Point	0.00	0.00				30.00	45.00	
	Upper Limit	200.00	Tolerance	83.00	48.00				35.00	50.00	
			Power	4.50	9.00				2.00	2.00	
			Merit Value	96.4%	83.8%				92.5%	99.0%	
Temperature Delta while operating in -100 to 100 environment (delta C)			Correlation		0.3	0.9	0.1				0.1
	Value	125.00	Function Type		Avoid	Avoid	Avoid				Opt
	Lower Limit	90.00	Neutral or Optimum Point		90.00	90.00	90.00				200.00
	Upper Limit	200.00	Tolerance		20.00	20.00	31.00				100.00
			Power		2.00	2.70	3.00				4.00
			Merit Value		75.4%	81.9%	59.0%				76.0%
Number of Power Bus Lines (number of bus bars)			Correlation	0.3		0.1	0.9		0.3	0.1	
	Value	4.00	Function Type	Opt		Opt	Avoid		Avoid	Avoid	
	Lower Limit	2.00	Neutral or Optimum Point	3.00		4.00	0.00		0.00	10.00	
	Upper Limit	10.00	Tolerance	2.15		2.00	2.30		2.70	4.20	
			Power	3.00		2.00	4.00		6.00	8.00	
			Merit Value	90.9%		100.0%	90.1%		91.4%	94.5%	
Volume (m^3)			Correlation	0.3				0.9			
	Value	0.03	Function Type	Opt				Avoid			
	Lower Limit	0.03	Neutral or Optimum Point	0.00				12.00			
	Upper Limit	10.00	Tolerance	8.00				6.00			
			Power	2.00				6.00			
			Merit Value	100.0%				98.4%			
Robotically Servicable Mass (%)			Correlation	0.9	0.3			0.1	0.1	0.9	
	Value	70.00	Function Type	Min	Opt			Min	Opt	Opt	
	Lower Limit	0.00	Neutral or Optimum Point	100.00	100.00			100.00	125.00	125.00	
	Upper Limit	85.00	Tolerance		70.00				80.00	80.00	
			Power	1.50	2.00			2.00	2.00	2.00	
			Merit Value	44.0%	84.5%			62.9%	67.9%	67.9%	
Probability of achiving >= 8 TRL after 6 years (%)			Correlation	0.9	0.3	0.1	0.1	0.9	0.3		0.9
	Value	75.00	Function Type	Opt	Opt	Opt	Opt	Opt	Opt		Opt
	Lower Limit	0.00	Neutral or Optimum Point	100.00	100.00	100.00	100.00	100.00	100.00		100.00
	Upper Limit	100.00	Tolerance	30.00	21.00	21.00	40.00	30.00	40.00		21.00
			Power	1.50	1.50	1.50	1.50	1.50	1.50		1.50
			Merit Value	56.8%	43.5%	43.5%	66.9%	56.8%	66.9%		43.5%
Probability of achiving >= 8 TRL after 3 years (%)			Correlation	0.9	0.3	0.1	0.1	0.9	0.3		0.9
	Value	50.00	Function Type	Opt	Opt	Opt	Opt	Opt	Opt		Opt
	Lower Limit	0.00	Neutral or Optimum Point	100.00	100.00	100.00	100.00	100.00	100.00		100.00
	Upper Limit	100.00	Tolerance	40.00	38.00	38.00	45.00	40.00	45.00		38.00
			Power	2.00	2.00	2.00	2.00	2.00	2.00		2.00
			Merit Value	39.0%	36.6%	36.6%	44.8%	39.0%	44.8%		36.6%
Fault Tolerance Design (# faults that lead to catastrophic failure)			Correlation	0.1	0.3	0.3			0.9		0.3
	Value	3.00	Function Type	Opt	Avoid	Avoid			Avoid		Avoid
	Lower Limit	1.00	Neutral or Optimum Point	2.00	0.00	0.00			0.00		0.00
	Upper Limit	8.00	Tolerance	1.00	1.40	1.40			1.40		1.40
			Power	2.00	6.00	6.00			6.00		6.00
			Merit Value	50.0%	99.0%	99.0%			99.0%		99.0%
Power Output (W)			Correlation		0.1	0.3	0.9				
	Value	2000.00	Function Type		Opt	Opt	Opt				
	Lower Limit	200.00	Neutral or Optimum Point		200.00	200.00	2000.00				
	Upper Limit	10000.00	Tolerance		10000.00	10000.00	550.00				
			Power		1.00	1.00	2.00				
			Merit Value		84.7%	84.7%	100.0%				

Notes: 305kg x 55W/kg >> maximum necessary power output (1750W) however power system weight here did not disambiguate between redundancy and versatility features which may not be related to power, so reducing the weight substantially lower will hinder ODM in this CODA setup. Note 2000W is optimal ODM.

Appendix 19: CODA matrix for Robotic Arm power system (MIM)

MIM + Optical Casimir Cavity		Overall Design Merit (ODM)	77.5%	Must Meet Weight Requirements	Long Operating Life	Excellent Thermal Survivability	High Versatility (Varying Load Conditions)	Must Meet Volumetric Requirements	High Redundancy (Multiple Independent Systems)	High Serviceability	High Technology Readiness Level
			Normalized Weights	19%	8%	14%	8%	8%	22%	11%	8%
Engineering Characteristics (EC's)											
Power System Weight (kg)			Correlation	0.9		0.1	0.3	0.3	0.9		
	Value	290.00	Function Type	Opt		Max	Max	Opt	Max		
	Lower Limit	50.00	Neutral or Optimum Point	0.00		300.00	300.00	0.00	130.00		
	Upper Limit	500.00	Tolerance	400.00				450.00			
			Power	8.00		4.00	4.00	6.00	2.00		
			Merit Value	92.9%		73.6%	73.6%	93.3%	87.5%		
Designing for Operating Life (years)			Correlation		0.9	0.9	0.1		0.9	0.3	0.9
	Value	15.00	Function Type		Max	Max	Max		Opt	Max	Max
	Lower Limit	8.00	Neutral or Optimum Point		10.00	10.00	10.00		20.00	10.00	8.50
	Upper Limit	20.00	Tolerance						6.00		
			Power		2.40	2.40	2.40		10.00	2.40	2.00
			Merit Value		95.3%	95.3%	95.3%		86.1%	95.3%	100.0%
Mechanical Complexity (# Parts)			Correlation	0.1	0.3				0.1	0.3	
	Value	35.00	Function Type	Opt	Opt				Opt	Opt	
	Lower Limit	20.00	Neutral or Optimum Point	0.00	0.00				30.00	45.00	
	Upper Limit	200.00	Tolerance	83.00	48.00				35.00	50.00	
			Power	4.50	9.00				2.00	2.00	
			Merit Value	98.0%	94.5%				98.0%	96.2%	
Temperature Delta while operating in -100 to 100 environment (delta C)			Correlation		0.3	0.9	0.1				0.1
	Value	125.00	Function Type		Avoid	Avoid	Avoid				Opt
	Lower Limit	90.00	Neutral or Optimum Point		90.00	90.00	90.00				200.00
	Upper Limit	200.00	Tolerance		20.00	20.00	31.00				100.00
			Power		2.00	2.70	3.00				4.00
			Merit Value		75.4%	81.9%	59.0%				76.0%
Number of Power Bus Lines (number of bus bars)			Correlation	0.3		0.1	0.9		0.3	0.1	
	Value	4.00	Function Type	Opt		Opt	Avoid		Avoid	Avoid	
	Lower Limit	2.00	Neutral or Optimum Point	3.00		4.00	0.00		0.00	10.00	
	Upper Limit	10.00	Tolerance	2.15		2.00	2.30		2.70	4.20	
			Power	3.00		2.00	4.00		6.00	8.00	
			Merit Value	90.9%		100.0%	90.1%		91.4%	94.5%	
Volume (m^3)			Correlation	0.3				0.9			
	Value	0.03	Function Type	Opt				Avoid			
	Lower Limit	0.03	Neutral or Optimum Point	0.00				12.00			
	Upper Limit	10.00	Tolerance	8.00				6.00			
			Power	2.00				6.00			
			Merit Value	100.0%				98.4%			
Robotically Servicable Mass (%)			Correlation	0.9	0.3			0.1	0.1	0.9	
	Value	80.00	Function Type	Min	Opt			Min	Opt	Opt	
	Lower Limit	0.00	Neutral or Optimum Point	100.00	100.00			100.00	125.00	125.00	
	Upper Limit	85.00	Tolerance		70.00				80.00	80.00	
			Power	1.50	2.00			2.00	2.00	2.00	
			Merit Value	39.8%	92.5%			58.0%	76.0%	76.0%	
Probability of achiving >= 8 TRL after 6 years (%)			Correlation	0.9	0.3	0.1	0.1	0.9	0.3		0.9
	Value	75.00	Function Type	Opt	Opt	Opt	Opt	Opt	Opt		Opt
	Lower Limit	0.00	Neutral or Optimum Point	100.00	100.00	100.00	100.00	100.00	100.00		100.00
	Upper Limit	100.00	Tolerance	30.00	21.00	21.00	40.00	30.00	40.00		21.00
			Power	1.50	1.50	1.50	1.50	1.50	1.50		1.50
			Merit Value	56.8%	43.5%	43.5%	66.9%	56.8%	66.9%		43.5%
Probability of achiving >= 8 TRL after 3 years (%)			Correlation	0.9	0.3	0.1	0.1	0.9	0.3		0.9
	Value	50.00	Function Type	Opt	Opt	Opt	Opt	Opt	Opt		Opt
	Lower Limit	0.00	Neutral or Optimum Point	100.00	100.00	100.00	100.00	100.00	100.00		100.00
	Upper Limit	100.00	Tolerance	40.00	38.00	38.00	45.00	40.00	45.00		38.00
			Power	2.00	2.00	2.00	2.00	2.00	2.00		2.00
			Merit Value	39.0%	36.6%	36.6%	44.8%	39.0%	44.8%		36.6%
Fault Tolerance Design (# faults that lead to catastrophic failure)			Correlation	0.1	0.3	0.3			0.9		0.3
	Value	3.00	Function Type	Opt	Avoid	Avoid			Avoid		Avoid
	Lower Limit	1.00	Neutral or Optimum Point	2.00	0.00	0.00			0.00		0.00
	Upper Limit	8.00	Tolerance	1.00	1.40	1.40			1.40		1.40
			Power	2.00	6.00	6.00			6.00		6.00
			Merit Value	50.0%	99.0%	99.0%			99.0%		99.0%
Power Output (W)			Correlation		0.1	0.3	0.9				
	Value	2000.00	Function Type		Opt	Opt	Opt				
	Lower Limit	200.00	Neutral or Optimum Point		200.00	200.00	2000.00				
	Upper Limit	10000.00	Tolerance		10000.00	10000.00	550.00				
			Power		1.00	1.00	2.00				
			Merit Value		84.7%	84.7%	100.0%				

Notes: 290kg x 1071W/kg >> maximum necessary power output (1750W) however power system weight here did not disambiguate between redundancy and versatility features which may not be related to power, so reducing the weight substantially lower will hinder ODM in this CODA setup. Note 2000W is optimal ODM.

Appendix 20: CODA matrix for Robotic Arm power system (FCO)

Ferroelectric Crystal Oscillator		Overall Design Merit (ODM)	80.2%	Must Meet Weight Requirements	Long Operating Life	Excellent Thermal Survivability	High Versatility (Varying Load Conditions)	Must Meet Volumetric Requirements	High Redundancy (Multiple Independent Systems)	High Serviceability	High Technology Readiness Level
			Normalized Weights	19%	8%	14%	8%	8%	22%	11%	8%
Engineering Characteristics (EC's)											
Power System Weight (kg)			Correlation	0.9		0.1	0.3	0.3	0.9		
	Value	**290.00**	Function Type	Opt		Max	Max	Opt	Max		
	Lower Limit	50.00	Neutral or Optimum Point	0.00		300.00	300.00	0.00	130.00		
	Upper Limit	500.00	Tolerance	400.00				450.00			
			Power	8.00		4.00	4.00	6.00	2.00		
			Merit Value	92.9%		73.6%	73.6%	93.3%	87.5%		
Designing for Operating Life (years)			Correlation		0.9	0.9	0.1		0.9	0.3	0.9
	Value	**20.00**	Function Type		Max	Max	Max		Opt	Max	Max
	Lower Limit	8.00	Neutral or Optimum Point		10.00	10.00	10.00		20.00	10.00	8.50
	Upper Limit	20.00	Tolerance						6.00		
			Power		2.40	2.40	2.40		10.00	2.40	2.00
			Merit Value		99.5%	99.5%	99.5%		100.0%	99.5%	100.0%
Mechanical Complexity (# Parts)			Correlation	0.1	0.3				0.1	0.3	
	Value	**45.00**	Function Type	Opt	Opt				Opt	Opt	
	Lower Limit	20.00	Neutral or Optimum Point	0.00	0.00				30.00	45.00	
	Upper Limit	200.00	Tolerance	83.00	48.00				35.00	50.00	
			Power	4.50	9.00				2.00	2.00	
			Merit Value	94.0%	64.1%				84.5%	100.0%	
Temperature Delta while operating in -100 to 100 environment (delta C)			Correlation		0.3	0.9	0.1				0.1
	Value	**100.00**	Function Type		Avoid	Avoid	Avoid				Opt
	Lower Limit	90.00	Neutral or Optimum Point		90.00	90.00	90.00				200.00
	Upper Limit	200.00	Tolerance		20.00	20.00	31.00				100.00
			Power		2.00	2.70	3.00				4.00
			Merit Value		20.0%	13.3%	3.2%				50.0%
Number of Power Bus Lines (number of bus bars)			Correlation	0.3		0.1	0.9		0.3	0.1	
	Value	**4.00**	Function Type	Opt		Opt	Avoid		Avoid	Avoid	
	Lower Limit	2.00	Neutral or Optimum Point	3.00		4.00	0.00		0.00	10.00	
	Upper Limit	10.00	Tolerance	2.15		2.00	2.30		2.70	4.20	
			Power	3.00		2.00	4.00		6.00	8.00	
			Merit Value	90.9%		100.0%	90.1%		91.4%	94.5%	
Volume (m^3)			Correlation	0.3				0.9			
	Value	**0.03**	Function Type	Opt				Avoid			
	Lower Limit	0.03	Neutral or Optimum Point	0.00				12.00			
	Upper Limit	10.00	Tolerance	8.00				6.00			
			Power	2.00				6.00			
			Merit Value	100.0%				98.4%			
Robotically Servicable Mass (%)			Correlation	0.9	0.3			0.1	0.1	0.9	
	Value	**60.00**	Function Type	Min	Opt			Min	Opt	Opt	
	Lower Limit	0.00	Neutral or Optimum Point	100.00	100.00			100.00	125.00	125.00	
	Upper Limit	85.00	Tolerance		70.00				80.00	80.00	
			Power	1.50	2.00			2.00	2.00	2.00	
			Merit Value	49.1%	75.4%			68.5%	60.2%	60.2%	
Probability of achiving >= 8 TRL after 6 years (%)			Correlation	0.9	0.3	0.1	0.1	0.9	0.3		0.9
	Value	**90.00**	Function Type	Opt	Opt	Opt	Opt	Opt	Opt		Opt
	Lower Limit	0.00	Neutral or Optimum Point	100.00	100.00	100.00	100.00	100.00	100.00		100.00
	Upper Limit	100.00	Tolerance	30.00	21.00	21.00	40.00	30.00	40.00		21.00
			Power	1.50	1.50	1.50	1.50	1.50	1.50		1.50
			Merit Value	83.9%	75.3%	75.3%	88.9%	83.9%	88.9%		75.3%
Probability of achiving >= 8 TRL after 3 years (%)			Correlation	0.9	0.3	0.1	0.1	0.9	0.3		0.9
	Value	**70.00**	Function Type	Opt	Opt	Opt	Opt	Opt	Opt		Opt
	Lower Limit	0.00	Neutral or Optimum Point	100.00	100.00	100.00	100.00	100.00	100.00		100.00
	Upper Limit	100.00	Tolerance	40.00	38.00	38.00	45.00	40.00	45.00		38.00
			Power	2.00	2.00	2.00	2.00	2.00	2.00		2.00
			Merit Value	64.0%	61.6%	61.6%	69.2%	64.0%	69.2%		61.6%
Fault Tolerance Design (# faults that lead to catastrophic failure)			Correlation	0.1	0.3	0.3			0.9		0.3
	Value	**3.00**	Function Type	Opt	Avoid	Avoid			Avoid		Avoid
	Lower Limit	1.00	Neutral or Optimum Point	2.00	0.00	0.00			0.00		0.00
	Upper Limit	8.00	Tolerance	1.00	1.40	1.40			1.40		1.40
			Power	2.00	6.00	6.00			6.00		6.00
			Merit Value	50.0%	99.0%	99.0%			99.0%		99.0%
Power Output (W)			Correlation		0.1	0.3	0.9				
	Value	**2000.00**	Function Type		Opt	Opt	Opt				
	Lower Limit	200.00	Neutral or Optimum Point		200.00	200.00	2000.00				
	Upper Limit	10000.00	Tolerance		10000.00	10000.00	550.00				
			Power		1.00	1.00	2.00				
			Merit Value		84.7%	84.7%	100.0%				

Notes: 290kg x 1000W/kg >> maximum necessary power output (1750W) however power system weight here did not disambiguate between redundancy and versatility features which may not be related to power, so reducing the weight substantially lower will hinder ODM in this CODA setup. Note 2000W is optimal ODM.

Appendix 21: CODA matrix for Combine Harvester power system (Graphene Harvester)

Graphene Harvester		Overall Design Merit (ODM)	80.1%	High Versatility	High Reliability	High Fuel Efficiency	Good Machine Data Accuracy	High Temp High Altitude Efficiency	High combustibility resistance	Should have easy Maintenance	Must meet Volumetric requirements	Must meet required Energy Balance
			Normalized Weights	16%	13%	9%	4%	4%	16%	4%	18%	16%
Engineering Characteristics (EC's)												
Weight Goals (kg)			Correlation	0.1	0.1						0.3	
	Value	7000.00	Function Type	Opt	Avoid						Min	
	Lower Limit	4000.00	Neutral or Optimum Point	4000.00	0.00						7000.00	
	Upper Limit	7000.00	Tolerance	2500.00	4160.00							
			Power	4.00	3.00						1.60	
			Merit Value	32.5%	82.7%						37.5%	
Versatility Index (idx)			Correlation	0.9	0.3	0.3	0.1	0.9	0.3	0.3	0.1	0.3
	Value	0.80	Function Type	Opt	Opt	Max	Max	Opt	Avoid	Max	Max	Max
	Lower Limit	0.00	Neutral or Optimum Point	1.00	1.00	0.25	0.50	1.00	0.00	0.25	0.20	0.30
	Upper Limit	1.00	Tolerance	0.30	0.26			0.20	0.70			
			Power	3.00	2.00	2.00	2.00	4.00	12.00	4.00	2.00	2.00
			Merit Value	77.1%	62.8%	89.1%	67.0%	50.0%	83.2%	98.8%	93.8%	84.3%
Power (KW)			Correlation	0.9	0.1	0.1		0.3				0.9
	Value	363.00	Function Type	Opt	Min	Opt		Min				Avoid
	Lower Limit	200.00	Neutral or Optimum Point	700.00	600.00	8000.00		800.00				0.00
	Upper Limit	700.00	Tolerance	348.00		15000.00						150.00
			Power	4.00	4.00	2.00		2.00				2.00
			Merit Value	53.2%	96.7%	79.4%		92.2%				85.4%
Altitude Rating (feet)			Correlation	0.3	0.1	0.3		0.9	0.1			
	Value	7000.00	Function Type	Max	Max	Opt		Opt	Opt			
	Lower Limit	0.00	Neutral or Optimum Point	1500.00	1500.00	7000.00		7000.00	7000.00			
	Upper Limit	7000.00	Tolerance			3000.00		3000.00	3000.00			
			Power	2.00	2.00	8.00		8.00	8.00			
			Merit Value	96.1%	96.1%	100.0%		100.0%	100.0%			
Avg Consumable Fuel Input (liters/hour)			Correlation	0.9		0.9		0.3	0.3			0.9
	Value	0.00	Function Type	Opt		Opt		Opt	Opt			Opt
	Lower Limit	0.00	Neutral or Optimum Point	0.00		0.00		0.00	0.00			0.00
	Upper Limit	200.00	Tolerance	80.00		80.00		80.00	80.00			126.00
			Power	4.00		4.00		4.00	4.00			4.00
			Merit Value	100.0%		100.0%		100.0%	100.0%			100.0%
Failure Rate (MTBF-hours)			Correlation	0.3	0.9		0.3	0.1	0.9	0.9		
	Value	2000.00	Function Type	Avoid	Avoid		Avoid	Opt	Opt	Avoid		
	Lower Limit	0.00	Neutral or Optimum Point	0.00	0.00		0.00	2000.00	2000.00	0.00		
	Upper Limit	2000.00	Tolerance	460.00	460.00		250.00	1650.00	1000.00	350.00		
			Power	2.50	2.50		2.00	2.00	8.00	4.00		
			Merit Value	97.5%	97.5%		98.5%	100.0%	100.0%	99.9%		
Sensor Reporting Index (Coverage_Index*Bandwidth_Index)			Correlation	0.1	0.3	0.1	0.9	0.1	0.1	0.3		
	Value	0.81	Function Type	Max	Max	Max	Max	Max	Opt	Max		
	Lower Limit	0.00	Neutral or Optimum Point	0.50	0.50	0.50	0.50	0.50	1.00	0.50		
	Upper Limit	1.00	Tolerance						0.50			
			Power	6.00	6.00	6.00	6.00	6.00	6.00	6.00		
			Merit Value	94.5%	94.5%	94.5%	94.5%	94.5%	99.7%	94.5%		
Use of Advanced Materials (%)			Correlation	0.1	0.9	0.3		0.1	0.9	0.3	0.1	0.3
	Value	0.70	Function Type	Max	Max	Max		Max	Opt	Min	Max	Max
	Lower Limit	0.00	Neutral or Optimum Point	0.65	0.35	0.50		0.50	1.00	0.50	0.50	0.50
	Upper Limit	1.00	Tolerance						0.60			
			Power	6.00	5.00	5.00		5.00	2.00	2.00	4.00	5.00
			Merit Value	85.5%	96.0%	89.5%		89.5%	80.0%	39.0%	85.6%	89.5%
Tribal Knowledge (%)			Correlation	0.3	0.9	0.1	0.3	0.1	0.3	0.9	0.1	0.3
	Value	0.56	Function Type	Opt	Opt	Opt	Opt	Opt	Opt	Opt	Opt	Opt
	Lower Limit	0.00	Neutral or Optimum Point	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Upper Limit	1.00	Tolerance	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			Power	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
			Merit Value	17.8%	17.8%	17.8%	17.8%	17.8%	17.8%	17.8%	17.8%	17.8%
Volumetric (m^3)			Correlation						0.3	0.3	0.9	
	Value	3.80	Function Type						Avoid	Avoid	Avoid	
	Lower Limit	0.00	Neutral or Optimum Point						9.00	9.00	9.00	
	Upper Limit	9.00	Tolerance						1.50	1.50	1.50	
			Power						4.00	4.00	4.00	
			Merit Value						99.3%	99.3%	99.3%	

Notes: Due to lower power density of graphene harvester, weight was maxed out at 7000kg resulting in a maximum power of 55.81W/kg x 6500 = 363kW. 500kg is subtracted from 7000kg to account for electric powertrain components. Volumetric of 3.8m^3 comes from 363kW divided by 96kW/m^3.

Appendix 22: CODA matrix for Combine Harvester power system (MIM)

MIM + Optical Casimir Cavity

Overall Design Merit (ODM): 84.6%

Engineering Characteristics (EC's)				High Versatility	High Reliability	High Fuel Efficiency	Good Machine Data Accuracy	High Temp High Altitude Efficiency	High combustibility resistance	Should have easy Maintenance	Must meet Volumetric requirements	Must meet required Energy Balance
			Normalized Weights	16%	13%	9%	4%	4%	16%	4%	18%	16%
Weight Goals (kg)			Correlation	0.1	0.1						0.3	
	Value	**4000.00**	Function Type	Opt	Avoid						Min	
	Lower Limit	4000.00	Neutral or Optimum Point	4000.00	0.00						7000.00	
	Upper Limit	7000.00	Tolerance	2500.00	4160.00							
			Power	4.00	3.00						1.60	
			Merit Value	100.0%	47.1%						100.0%	
Versatility Index (idx)			Correlation	0.9	0.3	0.3	0.1	0.9	0.3	0.3	0.1	0.3
	Value	**0.90**	Function Type	Opt	Opt	Max	Max	Opt	Avoid	Max	Max	Max
	Lower Limit	0.00	Neutral or Optimum Point	1.00	1.00	0.25	0.50	1.00	0.00	0.25	0.20	0.30
	Upper Limit	1.00	Tolerance	0.30	0.26			0.20	0.70			
			Power	3.00	2.00	2.00	2.00	4.00	12.00	4.00	2.00	2.00
			Merit Value	96.4%	87.1%	91.8%	71.3%	94.1%	95.3%	99.3%	95.6%	87.5%
Power (KW)			Correlation	0.9	0.1	0.1		0.3				0.9
	Value	**700.00**	Function Type	Opt	Min	Opt		Min				Avoid
	Lower Limit	200.00	Neutral or Optimum Point	700.00	600.00	8000.00		800.00				0.00
	Upper Limit	700.00	Tolerance	348.00		15000.00						150.00
			Power	4.00	4.00	2.00		2.00				2.00
			Merit Value	100.0%	67.0%	80.9%		56.5%				95.6%
Altitude Rating (feet)			Correlation	0.3	0.1	0.3		0.9	0.1			
	Value	**7000.00**	Function Type	Max	Max	Opt		Opt	Opt			
	Lower Limit	0.00	Neutral or Optimum Point	1500.00	1500.00	7000.00		7000.00	7000.00			
	Upper Limit	7000.00	Tolerance			3000.00		3000.00	3000.00			
			Power	2.00	2.00	8.00		8.00	8.00			
			Merit Value	96.1%	96.1%	100.0%		100.0%	100.0%			
Avg Consumable Fuel Input (liters/hour)			Correlation	0.9		0.9		0.3	0.3			0.9
	Value	**0.00**	Function Type	Opt		Opt		Opt	Opt			Opt
	Lower Limit	0.00	Neutral or Optimum Point	0.00		0.00		0.00	0.00			0.00
	Upper Limit	200.00	Tolerance	80.00		80.00		80.00	80.00			126.00
			Power	4.00		4.00		4.00	4.00			4.00
			Merit Value	100.0%		100.0%		100.0%	100.0%			100.0%
Failure Rate (MTBF-hours)			Correlation	0.3	0.9		0.3	0.1	0.9	0.9		
	Value	**2000.00**	Function Type	Avoid	Avoid		Avoid	Opt	Opt	Avoid		
	Lower Limit	0.00	Neutral or Optimum Point	0.00	0.00		0.00	2000.00	2000.00	0.00		
	Upper Limit	2000.00	Tolerance	460.00	460.00		250.00	1650.00	1000.00	350.00		
			Power	2.50	2.50		2.00	2.00	8.00	4.00		
			Merit Value	97.5%	97.5%		98.5%	100.0%	100.0%	99.9%		
Sensor Reporting Index (Coverage_Index*Bandwidth_Index)			Correlation	0.1	0.3	0.1	0.9	0.1	0.1	0.3		
	Value	**0.81**	Function Type	Max	Max	Max	Max	Max	Opt	Max		
	Lower Limit	0.00	Neutral or Optimum Point	0.50	0.50	0.50	0.50	0.50	1.00	0.50		
	Upper Limit	1.00	Tolerance						0.50			
			Power	6.00	6.00	6.00	6.00	6.00	6.00	6.00		
			Merit Value	94.5%	94.5%	94.5%	94.5%	94.5%	99.7%	94.5%		
Use of Advanced Materials (%)			Correlation	0.1	0.9	0.3		0.1	0.9	0.3	0.1	0.3
	Value	**0.70**	Function Type	Max	Max	Max		Max	Opt	Min	Max	Max
	Lower Limit	0.00	Neutral or Optimum Point	0.65	0.35	0.50		0.50	1.00	0.50	0.50	0.50
	Upper Limit	1.00	Tolerance						0.60			
			Power	6.00	5.00	5.00		5.00	2.00	2.00	4.00	5.00
			Merit Value	85.5%	96.0%	89.5%		89.5%	80.0%	39.0%	85.6%	89.5%
Tribal Knowledge (%)			Correlation	0.3	0.9	0.1	0.3	0.1	0.3	0.9	0.1	0.3
	Value	**0.24**	Function Type	Opt	Opt	Opt	Opt	Opt	Opt	Opt	Opt	Opt
	Lower Limit	0.00	Neutral or Optimum Point	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Upper Limit	1.00	Tolerance	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			Power	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
			Merit Value	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%
Volumetric (m^3)			Correlation						0.3	0.3	0.9	
	Value	**0.42**	Function Type						Avoid	Avoid	Avoid	
	Lower Limit	0.00	Neutral or Optimum Point						9.00	9.00	9.00	
	Upper Limit	9.00	Tolerance						1.50	1.50	1.50	
			Power						4.00	4.00	4.00	
			Merit Value						99.9%	99.9%	99.9%	

Notes: Due to higher power density of MIM device, weight was reduced to the minimum constraint of 4000kg resulting in a maximum power of 1071W/kg x 3500 = 3749kW >> 700kW. 4000kg - 500kg to account for electric powertrain components. Volumetric of $0.42m^3$ comes from 700kW divided by $1680kW/m^3$.

Appendix 23: CODA matrix for Combine Harvester power system (FCO)

Ferroelectric Crystal Oscillator		Overall Design Merit (ODM)	85.1%	High Versatility	High Reliability	High Fuel Efficiency	Good Machine Data Accuracy	High Temp High Altitude Efficiency	High combustibility resistance	Should have easy Maintenance	Must meet Volumetric requirements	Must meet required Energy Balance
			Normalized Weights	16%	13%	9%	4%	4%	16%	4%	18%	16%
Engineering Characteristics (EC's)												
Weight Goals (kg)			Correlation	0.1	0.1						0.3	
	Value	**4000.00**	Function Type	Opt	Avoid						Min	
	Lower Limit	4000.00	Neutral or Optimum Point	4000.00	0.00						7000.00	
	Upper Limit	7000.00	Tolerance	2500.00	4160.00							
			Power	4.00	3.00						1.60	
			Merit Value	100.0%	47.1%						100.0%	
Versatility Index (idx)			Correlation	0.9	0.3	0.3	0.1	0.9	0.3	0.3	0.1	0.3
	Value	**0.90**	Function Type	Opt	Opt	Max	Max	Opt	Avoid	Max	Max	Max
	Lower Limit	0.00	Neutral or Optimum Point	1.00	1.00	0.25	0.50	1.00	0.00	0.25	0.20	0.30
	Upper Limit	1.00	Tolerance	0.30	0.26			0.20	0.70			
			Power	3.00	2.00	2.00	2.00	4.00	12.00	4.00	2.00	2.00
			Merit Value	96.4%	87.1%	91.8%	71.3%	94.1%	95.3%	99.3%	95.6%	87.5%
Power (KW)			Correlation	0.9	0.1	0.1		0.3				0.9
	Value	**700.00**	Function Type	Opt	Min	Opt		Min				Avoid
	Lower Limit	200.00	Neutral or Optimum Point	700.00	600.00	8000.00		800.00				0.00
	Upper Limit	700.00	Tolerance	348.00		15000.00						150.00
			Power	4.00	4.00	2.00		2.00				2.00
			Merit Value	100.0%	67.0%	80.9%		56.5%				95.6%
Altitude Rating (feet)			Correlation	0.3	0.1	0.3		0.9	0.1			
	Value	**7000.00**	Function Type	Max	Max	Opt		Opt	Opt			
	Lower Limit	0.00	Neutral or Optimum Point	1500.00	1500.00	7000.00		7000.00	7000.00			
	Upper Limit	7000.00	Tolerance			3000.00		3000.00	3000.00			
			Power	2.00	2.00	8.00		8.00	8.00			
			Merit Value	96.1%	96.1%	100.0%		100.0%	100.0%			
Avg Consumable Fuel Input (liters/hour)			Correlation	0.9		0.9		0.3	0.3			0.9
	Value	**0.00**	Function Type	Opt		Opt		Opt	Opt			Opt
	Lower Limit	0.00	Neutral or Optimum Point	0.00		0.00		0.00	0.00			0.00
	Upper Limit	200.00	Tolerance	80.00		80.00		80.00	80.00			126.00
			Power	4.00		4.00		4.00	4.00			4.00
			Merit Value	100.0%		100.0%		100.0%	100.0%			100.0%
Failure Rate (MTBF-hours)			Correlation	0.3	0.9		0.3	0.1	0.9	0.9		
	Value	**2000.00**	Function Type	Avoid	Avoid		Avoid	Opt	Opt	Avoid		
	Lower Limit	0.00	Neutral or Optimum Point	0.00	0.00		0.00	2000.00	2000.00	0.00		
	Upper Limit	2000.00	Tolerance	460.00	460.00		250.00	1650.00	1000.00	350.00		
			Power	2.50	2.50		2.00	2.00	8.00	4.00		
			Merit Value	97.5%	97.5%		98.5%	100.0%	100.0%	99.9%		
Sensor Reporting Index (Coverage_Index*Bandwidth_Index)			Correlation	0.1	0.3	0.1	0.9	0.1	0.1	0.3		
	Value	**0.60**	Function Type	Max	Max	Max	Max	Max	Opt	Max		
	Lower Limit	0.00	Neutral or Optimum Point	0.50	0.50	0.50	0.50	0.50	1.00	0.50		
	Upper Limit	1.00	Tolerance						0.50			
			Power	6.00	6.00	6.00	6.00	6.00	6.00	6.00		
			Merit Value	88.4%	88.4%	88.4%	88.4%	88.4%	79.2%	88.4%		
Use of Advanced Materials (%)			Correlation	0.1	0.9	0.3		0.1	0.9	0.3	0.1	0.3
	Value	**0.90**	Function Type	Max	Max	Max		Max	Opt	Min	Max	Max
	Lower Limit	0.00	Neutral or Optimum Point	0.65	0.35	0.50		0.50	1.00	0.50	0.50	0.50
	Upper Limit	1.00	Tolerance						0.60			
			Power	6.00	5.00	5.00		5.00	2.00	2.00	4.00	5.00
			Merit Value	91.6%	98.4%	94.5%		94.5%	97.3%	32.0%	91.8%	94.5%
Tribal Knowledge (%)			Correlation	0.3	0.9	0.1	0.3	0.1	0.3	0.9	0.1	0.3
	Value	**0.08**	Function Type	Opt	Opt	Opt	Opt	Opt	Opt	Opt	Opt	Opt
	Lower Limit	0.00	Neutral or Optimum Point	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Upper Limit	1.00	Tolerance	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
			Power	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
			Merit Value	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%	1.1%
Volumetric (m^3)			Correlation						0.3	0.3	0.9	
	Value	**0.17**	Function Type						Avoid	Avoid	Avoid	
	Lower Limit	0.00	Neutral or Optimum Point						9.00	9.00	9.00	
	Upper Limit	9.00	Tolerance						1.50	1.50	1.50	
			Power						4.00	4.00	4.00	
			Merit Value						99.9%	99.9%	99.9%	

Notes: Due to higher power density of FCO device, weight was reduced to the minimum constraint of 4000kg resulting in a maximum power of 1000W/kg x 3500 = 3500kW >> 700kW. 4000kg - 500kg to account for electric powertrain components. Volumetric of 0.17m^3 comes from 700kW divided by 4065kW/m^3.

Appendix 24: CODA matrix for Emergency Helicopter power system (Graphene Harvester)

Graphene Harvester

				Good Med/High Energy Content	High Power	High Safety	High One-Time Use Reliability	Long Shelf Life	Very low operating temperature	Good Vibration Resistance	High Altitude Operation	High Shock Resistance/Survivability	Good External Radiation Protection	Water and Particle ingress protections
Overall Design Merit (ODM)			**76.1%**											
			Normalized Weights	9%	14%	15%	14%	6%	8%	12%	6%	8%	6%	3%
Engineering Characteristics (EC's)														
Power System Weight (kg)			Correlation	0.9	0.9	0.9								
	Value	**102.50**	Function Type	Min	Opt	Opt								
	Lower Limit	0.00	Neutral or Optimum Point	266.00	0.00	0.00								
	Upper Limit	200.00	Tolerance		240.00	120.00								
			Power	2.00	2.00	2.00								
			Merit Value	83.5%	84.6%	57.8%								
RF Shielding Weight (kg)			Correlation										0.9	
	Value	**3.75**	Function Type										Opt	
	Lower Limit	0.00	Neutral or Optimum Point										16.00	
	Upper Limit	16.00	Tolerance										8.00	
			Power										2.00	
			Merit Value										29.9%	
Safety System Weight (kg)			Correlation			0.9								
	Value	**2.00**	Function Type			Opt								
	Lower Limit	0.00	Neutral or Optimum Point			25.00								
	Upper Limit	25.00	Tolerance			14.00								
			Power			2.00								
			Merit Value			27.0%								
Thermal System Weight (kg)			Correlation						0.9					
	Value	**11.75**	Function Type						Opt					
	Lower Limit	0.00	Neutral or Optimum Point						16.00					
	Upper Limit	32.00	Tolerance						14.00					
			Power						2.00					
			Merit Value						91.6%					
Specific Power Rating (W/kg)			Correlation	0.3	0.9	0.9								
	Value	**5721.00**	Function Type	Min	Opt	Opt								
	Lower Limit	0.00	Neutral or Optimum Point	11000.00	9000.00	8000.00								
	Upper Limit	10000.00	Tolerance		3000.00	3000.00								
			Power	2.00	2.00	2.00								
			Merit Value	73.6%	45.6%	63.4%								
Energy Density (Wh/kg)			Correlation	0.9	0.9	0.9								
	Value	**300.00**	Function Type	Opt	Max	Max								
	Lower Limit	0.00	Neutral or Optimum Point	300.00	65.00	90.00								
	Upper Limit	300.00	Tolerance	100.00										
			Power	2.00	2.00	2.00								
			Merit Value	100.0%	95.9%	90.1%								
Inches Per Sec Rating (IPS_rms)			Correlation			0.9	0.3			0.9				
	Value	**2.60**	Function Type			Opt	Max			Max				
	Lower Limit	0.00	Neutral or Optimum Point			2.50	0.30			0.30				
	Upper Limit	3.00	Tolerance			1.50								
			Power			2.00	2.00			2.00				
			Merit Value			99.6%	99.8%			99.8%				
Failure Rate (MTBF-hours)			Correlation	0.1	0.1	0.9	0.9		0.1	0.3	0.1	0.1	0.1	0.1
	Value	**150000.00**	Function Type	Max	Max	Max	Max		Max	Max	Max	Max	Max	Max
	Lower Limit	1000.00	Neutral or Optimum Point	30000.00	30000.00	37800.00	37800.00		18000.00	37800.00	37800.00	11600.00	37800.00	37800.00
	Upper Limit	150000.00	Tolerance											
			Power	2.00	2.00	2.00	2.00		2.00	2.00	2.00	2.00	2.00	2.00
			Merit Value	97.2%	97.2%	94.0%	94.0%		99.8%	94.0%	94.0%	100.0%	94.0%	94.0%
Expected Shelf Life (years)			Correlation	0.1		0.3	0.3	0.9						0.9
	Value	**15.00**	Function Type	Max		Max	Max	Opt						Max
	Lower Limit	0.00	Neutral or Optimum Point	5.00		4.30	4.30	12.00						3.70
	Upper Limit	15.00	Tolerance					6.00						
			Power	2.00		2.00	2.00	2.00						2.00
			Merit Value	87.5%		91.1%	91.1%	80.0%						94.0%
Component Rating Confidence (%)			Correlation			0.9	0.9	0.3	0.1	0.9	0.3	0.1		
	Value	**49.00**	Function Type			Opt	Opt	Opt	Opt	Opt	Opt	Opt		
	Lower Limit	0.00	Neutral or Optimum Point			100.00	100.00	100.00	100.00	100.00	100.00	100.00		
	Upper Limit	100.00	Tolerance			45.00	45.00	30.00	20.00	45.00	70.00	40.00		
			Power			2.00	2.00	2.00	2.00	2.00	2.00	2.00		
			Merit Value			43.8%	43.8%	25.7%	13.3%	43.8%	65.3%	38.1%		
Shock Rating (g's)			Correlation			0.3	0.1					0.9		
	Value	**60.00**	Function Type			Opt	Opt					Opt		
	Lower Limit	0.00	Neutral or Optimum Point			60.00	60.00					60.00		
	Upper Limit	60.00	Tolerance			70.00	70.00					70.00		
			Power			2.00	2.00					2.00		
			Merit Value			100.0%	100.0%					100.0%		
Rated Altitude (kPa)			Correlation			0.1					0.9			
	Value	**55.00**	Function Type			Opt					Opt			
	Lower Limit	50.00	Neutral or Optimum Point			50.00					50.00			
	Upper Limit	150.00	Tolerance			10.00					10.00			
			Power			2.00					2.00			
			Merit Value			80.0%					80.0%			

Notes: Weight minimized to 102.5kg x 55.81W/kg = 5721W. The remaining 17.5kg were optimally distributed between RF shielding, thermal, and safety system weight to maximize ODM.

Appendix 25: CODA matrix for Emergency Helicopter power system (MIM)

MIM + Optical Casimir Cavity

Overall Design Merit (ODM): 85.6%

Engineering Characteristics (EC's)				Good Med/High Energy Content	High Power	High Safety	High One-Time Use Reliability	Long Shelf Life	Very low operating temperature	Good Vibration Resistance	High Altitude Operation	High Shock Resistance/Survivability	Good External Radiation Protection	Water and Particle ingress protections
			Normalized Weights	9%	14%	15%	14%	6%	8%	12%	6%	8%	6%	3%
Power System Weight (kg)			Correlation	0.9	0.9	0.9								
	Value	7.50	Function Type	Min	Opt	Opt								
	Lower Limit	0.00	Neutral or Optimum Point	266.00	0.00	0.00								
	Upper Limit	200.00	Tolerance		240.00	120.00								
			Power	2.00	2.00	2.00								
			Merit Value	100.0%	99.9%	99.6%								
RF Shielding Weight (kg)			Correlation										0.9	
	Value	16.00	Function Type										Opt	
	Lower Limit	0.00	Neutral or Optimum Point										16.00	
	Upper Limit	16.00	Tolerance										8.00	
			Power										2.00	
			Merit Value										100.0%	
Safety System Weight (kg)			Correlation			0.9								
	Value	25.00	Function Type			Opt								
	Lower Limit	0.00	Neutral or Optimum Point			25.00								
	Upper Limit	25.00	Tolerance			14.00								
			Power			2.00								
			Merit Value			100.0%								
Thermal System Weight (kg)			Correlation						0.9					
	Value	16.00	Function Type						Opt					
	Lower Limit	0.00	Neutral or Optimum Point						16.00					
	Upper Limit	32.00	Tolerance						14.00					
			Power						2.00					
			Merit Value						100.0%					
Specific Power Rating (W/kg)			Correlation	0.3	0.9	0.9								
	Value	8000.00	Function Type	Min	Opt	Opt								
	Lower Limit	0.00	Neutral or Optimum Point	11000.00	9000.00	8000.00								
	Upper Limit	10000.00	Tolerance		3000.00	3000.00								
			Power	2.00	2.00	2.00								
			Merit Value	61.4%	90.0%	100.0%								
Energy Density (Wh/kg)			Correlation	0.9	0.9	0.9								
	Value	300.00	Function Type	Opt	Max	Max								
	Lower Limit	0.00	Neutral or Optimum Point	300.00	65.00	90.00								
	Upper Limit	300.00	Tolerance	100.00										
			Power	2.00	2.00	2.00								
			Merit Value	100.0%	95.9%	90.1%								
Inches Per Sec Rating (IPS_rms)			Correlation			0.9	0.3			0.9				
	Value	2.60	Function Type			Opt	Max			Max				
	Lower Limit	0.00	Neutral or Optimum Point			2.50	0.30			0.30				
	Upper Limit	3.00	Tolerance			1.50								
			Power			2.00	2.00			2.00				
			Merit Value			99.6%	99.8%			99.8%				
Failure Rate (MTBF-hours)			Correlation	0.1	0.1	0.9	0.9		0.1	0.3	0.1	0.1	0.1	0.1
	Value	150000.00	Function Type	Max	Max	Max	Max		Max	Max	Max	Max	Max	Max
	Lower Limit	1000.00	Neutral or Optimum Point	30000.00	30000.00	37800.00	37800.00		18000.00	37800.00	37800.00	11600.00	37800.00	37800.00
	Upper Limit	150000.00	Tolerance											
			Power	2.00	2.00	2.00	2.00		2.00	2.00	2.00	2.00	2.00	2.00
			Merit Value	97.2%	97.2%	94.0%	94.0%		99.8%	94.0%	94.0%	100.0%	94.0%	94.0%
Expected Shelf Life (years)			Correlation	0.1		0.3	0.3	0.9						0.9
	Value	15.00	Function Type	Max		Max	Max	Opt						Max
	Lower Limit	0.00	Neutral or Optimum Point	5.00		4.30	4.30	12.00						3.70
	Upper Limit	15.00	Tolerance					6.00						
			Power	2.00		2.00	2.00	2.00						2.00
			Merit Value	87.5%		91.1%	91.1%	80.0%						94.0%
Component Rating Confidence (%)			Correlation			0.9	0.9	0.3	0.1	0.9	0.3	0.1		
	Value	35.00	Function Type			Opt	Opt	Opt	Opt	Opt	Opt	Opt		
	Lower Limit	0.00	Neutral or Optimum Point			100.00	100.00	100.00	100.00	100.00	100.00	100.00		
	Upper Limit	100.00	Tolerance			45.00	45.00	30.00	20.00	45.00	70.00	40.00		
			Power			2.00	2.00	2.00	2.00	2.00	2.00	2.00		
			Merit Value			32.4%	32.4%	17.6%	8.6%	32.4%	53.7%	27.5%		
Shock Rating (g's)			Correlation			0.3	0.1					0.9		
	Value	60.00	Function Type			Opt	Opt					Opt		
	Lower Limit	0.00	Neutral or Optimum Point			60.00	60.00					60.00		
	Upper Limit	60.00	Tolerance			70.00	70.00					70.00		
			Power			2.00	2.00					2.00		
			Merit Value			100.0%	100.0%					100.0%		
Rated Altitude (kPa)			Correlation			0.1					0.9			
	Value	50.00	Function Type			Opt					Opt			
	Lower Limit	50.00	Neutral or Optimum Point			50.00					50.00			
	Upper Limit	150.00	Tolerance			10.00					10.00			
			Power			2.00					2.00			
			Merit Value			100.0%					100.0%			

Notes: Weight minimized to 7.5kg x 1071W/kg = 8000W. Leaving enough remaining weight to optimally distributed between RF shielding, thermal, and safety system weight to maximize ODM.

Appendix 26: CODA matrix for Emergency Helicopter power system (FCO)

Ferroelectric Crystal Oscillator

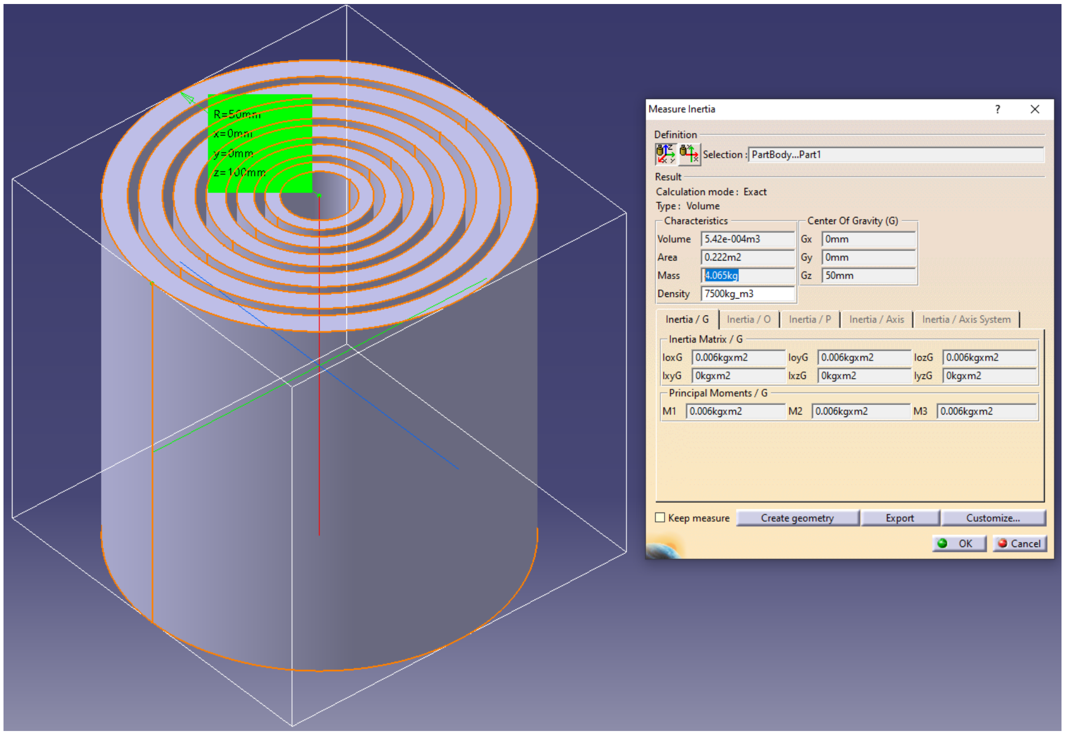
Overall Design Merit (ODM): 88.2%

Engineering Characteristics (EC's)				Good Med/High Energy Content	High Power	High Safety	High One-Time Use Reliability	Long Shelf Life	Very low operating temperature	Good Vibration Resistance	High Altitude Operation	High Shock Resistance/Survivability	Good External Radiation Protection	Water and Particle ingress protections
			Normalized Weights	9%	14%	15%	14%	6%	8%	12%	6%	8%	6%	3%
Power System Weight (kg)			Correlation	0.9	0.9	0.9								
	Value	8.00	Function Type	Min	Opt	Opt								
	Lower Limit	0.00	Neutral or Optimum Point	266.00	0.00	0.00								
	Upper Limit	200.00	Tolerance		240.00	120.00								
			Power	2.00	2.00	2.00								
			Merit Value	100.0%	99.9%	99.6%								
RF Shielding Weight (kg)			Correlation										0.9	
	Value	16.00	Function Type										Opt	
	Lower Limit	0.00	Neutral or Optimum Point										16.00	
	Upper Limit	16.00	Tolerance										8.00	
			Power										2.00	
			Merit Value										100.0%	
Safety System Weight (kg)			Correlation			0.9								
	Value	25.00	Function Type			Opt								
	Lower Limit	0.00	Neutral or Optimum Point			25.00								
	Upper Limit	25.00	Tolerance			14.00								
			Power			2.00								
			Merit Value			100.0%								
Thermal System Weight (kg)			Correlation						0.9					
	Value	16.00	Function Type						Opt					
	Lower Limit	0.00	Neutral or Optimum Point						16.00					
	Upper Limit	32.00	Tolerance						14.00					
			Power						2.00					
			Merit Value						100.0%					
Specific Power Rating (W/kg)			Correlation	0.3	0.9	0.9								
	Value	8000.00	Function Type	Min	Opt	Opt								
	Lower Limit	0.00	Neutral or Optimum Point	11000.00	9000.00	8000.00								
	Upper Limit	10000.00	Tolerance		3000.00	3000.00								
			Power	2.00	2.00	2.00								
			Merit Value	61.4%	90.0%	100.0%								
Energy Density (Wh/kg)			Correlation	0.9	0.9	0.9								
	Value	300.00	Function Type	Opt	Max	Max								
	Lower Limit	0.00	Neutral or Optimum Point	300.00	65.00	90.00								
	Upper Limit	300.00	Tolerance	100.00										
			Power	2.00	2.00	2.00								
			Merit Value	100.0%	95.9%	90.1%								
Inches Per Sec Rating (IPS_rms)			Correlation			0.9	0.3			0.9				
	Value	1.00	Function Type			Opt	Max			Max				
	Lower Limit	0.00	Neutral or Optimum Point			2.50	0.30			0.30				
	Upper Limit	3.00	Tolerance			1.50								
			Power			2.00	2.00			2.00				
			Merit Value			50.0%	90.1%			90.1%				
Failure Rate (MTBF-hours)			Correlation	0.1	0.1	0.9	0.9		0.1	0.3	0.1	0.1	0.1	0.1
	Value	150000.00	Function Type	Max	Max	Max	Max		Max	Max	Max	Max	Max	Max
	Lower Limit	1000.00	Neutral or Optimum Point	30000.00	30000.00	37800.00	37800.00		18000.00	37800.00	37800.00	11600.00	37800.00	37800.00
	Upper Limit	150000.00	Tolerance											
			Power	2.00	2.00	2.00	2.00		2.00	2.00	2.00	2.00	2.00	2.00
			Merit Value	97.2%	97.2%	94.0%	94.0%		99.8%	94.0%	94.0%	100.0%	94.0%	94.0%
Expected Shelf Life (years)			Correlation	0.1		0.3	0.3	0.9						0.9
	Value	15.00	Function Type	Max		Max	Max	Opt						Max
	Lower Limit	0.00	Neutral or Optimum Point	5.00		4.30	4.30	12.00						3.70
	Upper Limit	15.00	Tolerance					6.00						
			Power	2.00		2.00	2.00	2.00						2.00
			Merit Value	87.5%		91.1%	91.1%	80.0%						94.0%
Component Rating Confidence (%)			Correlation			0.9	0.9	0.3	0.1	0.9	0.3	0.1		
	Value	63.00	Function Type			Opt	Opt	Opt	Opt	Opt	Opt	Opt		
	Lower Limit	0.00	Neutral or Optimum Point			100.00	100.00	100.00	100.00	100.00	100.00	100.00		
	Upper Limit	100.00	Tolerance			45.00	45.00	30.00	20.00	45.00	70.00	40.00		
			Power			2.00	2.00	2.00	2.00	2.00	2.00	2.00		
			Merit Value			59.7%	59.7%	39.7%	22.6%	59.7%	78.2%	53.9%		
Shock Rating (g's)			Correlation			0.3	0.1					0.9		
	Value	60.00	Function Type			Opt	Opt					Opt		
	Lower Limit	0.00	Neutral or Optimum Point			60.00	60.00					60.00		
	Upper Limit	60.00	Tolerance			70.00	70.00					70.00		
			Power			2.00	2.00					2.00		
			Merit Value			100.0%	100.0%					100.0%		
Rated Altitude (kPa)			Correlation			0.1					0.9			
	Value	50.00	Function Type			Opt					Opt			
	Lower Limit	50.00	Neutral or Optimum Point			50.00					50.00			
	Upper Limit	150.00	Tolerance			10.00					10.00			
			Power			2.00					2.00			
			Merit Value			100.0%					100.0%			

Notes: Weight minimized to 8.0kg x 1000W/kg = 8000W. Leaving enough remaining weight to optimally distributed between RF shielding, thermal, and safety system weight to maximize ODM.

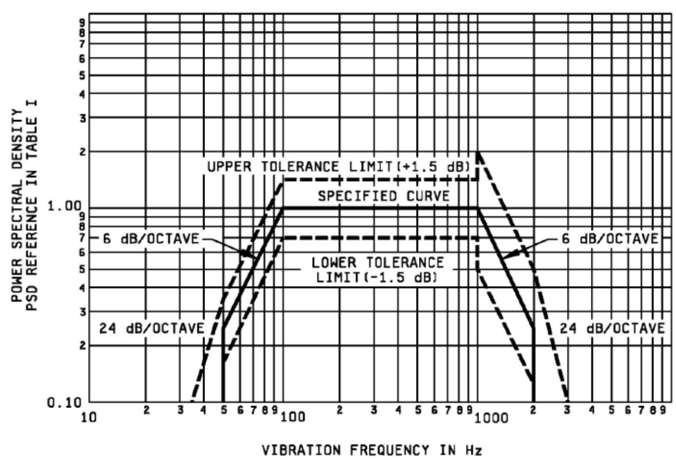
8.4 EC Estimation Details

Appendix 27: FCO Concentrically Stacked Concept



Source: Own representation (Based on M. Reid, personal communication, (6/24/2022))

Appendix 28: MIL-STD-883H random vibration test-curve envelope



Characteristics		
Test condition letter	Power spectral density	Overall rms G
A	.02	5.2
B	.04	7.3
C	.06	9.0
D	.1	11.6
E	.2	16.4
F	.3	20.0
G	.4	23.1
H	.6	28.4
J	1.0	36.6
K	1.5	44.8

Source: MIL-STD-883H

Appendix 29: IPS_{RMS} unit converter calculator

	A	B	C	D	E	F	G	H	I
2									
3	RANDOM		Crest Factor	3.0					
4	Frequency	Amplitude							
5	(Hz)	(G^2/Hz)	Slope (dB/Oct)			Accel area	Vel area	Disp area	
6	50	0.01							
7	100	0.04	6.00			1.1667E+00	5.0661E-06	2.5665E-11	
8	1000	0.04	0.00			3.6000E+01	9.1189E-06	8.5464E-12	
9	2,000	0.0100000	-6.00			2.0000E+01	2.9552E-07	4.9726E-15	
10									
11									
12									
13									
14									
15									
16									
17									
18									
19									
20									
21									
22									
23									
24									
25									
26					Total Random	5.7167E+01	1.4480E-05	3.4216E-11	
27					square root Random	7.5609	0.0038	0.0000	
28									
29			Random-only		accel=	7.5609 G_{RMS}			
30					accel=	22.6826 G_{PEAK}			
31						vel=	1.4692 in/s_{RMS}		
32						vel=	4.4076 in/s_{PEAK}		
33							disp=	0.0023 in_{RMS}	
34							disp=	0.0136 in_{pk-pk}	

Source: https://vibrationresearch.com/resources/random-rms-calculator/