ENERGY HARVESTING STRATEGIES AND UPCYCLING IN MANUFACTURING

By

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DECLARATION STATEMENT

I certify that the work submitted is my own and that any material derived or quoted from the published or unpublished work of other persons has been duly acknowledged (ref. UPR AS/C/6.1, Appendix I, Section 2 – Section on cheating and plagiarism)

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ABSTRACT

This thesis examines the interconnected domain of energy harvesting, modular component build, and upcycling strategies in manufacturing with the goal of achieving net-zero emissions. The research is grounded in the Design for X (DFX) paradigm, which integrates various design considerations to enhance product quality while minimising environmental impact.

The first part of the thesis investigates the application of radio frequency (RF) and thermoelectric generator (TEG) energy harvesting technologies in manufacturing settings. These technologies capture waste heat and electromagnetic radiation from industrial equipment and convert them into usable electricity, reducing the overall energy consumption of the manufacturing process.

The second part of the thesis explores modular component build, which enables easy replacement, upgrading, and servicing of components, thus reducing waste and prolonging product lifespan. This approach contributes to sustainable manufacturing and complements the energy harvesting aspect by minimising emissions.

The third part of the thesis examines upcycling, which involves repurposing waste materials into new products or components. This concept supports the circular economy and synergises with the energy harvesting and modular component build strategies to further reduce waste and emissions in manufacturing. The results reveal that upcycling can substantially enhance manufacturing sustainability.

Overall, this thesis emphasises the importance of integrating energy harvesting, modular component build, and upcycling strategies in manufacturing to achieve net-zero emissions. The findings contribute to the growing body of knowledge on sustainable manufacturing practices, offering valuable insights for manufacturers, policymakers, and researchers in the pursuit of net-zero emissions.

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LIST OF ACRONYMS

AZO - Aluminium Doped Zinc Oxide

CAD – Computer-Aided Design

CER - Certified Emission Reduction

CE - Conformité Européenne (French)

CN - Customer Need(s)

CNC – Computer Numerically Controlled

CSA - Climate Smart Agriculture

CVE – Collaborative Virtual Environment

DFA – Design for Assembly

DFD - Design for Deployment

DFM – Design for Manufacture

DFMA – Design for Manufacture and Assembly

DFQ - Design for Quality

DfX – Design for Excellence, or Design for X (where X can refer to any variable in product development)

DMU – Digital Mock-Up

DP - Design Parameter(s)

DR – Design Review

EA - Environmental Agency

EPA - Environmental Protection Agency

GHG – Greenhouse Gases

HSE - Health and Safety Executive

HVAC - Heating, Ventilation and Cooling

IEA - International Energy Agency

IPCC - International Panel on Climate Change

IR - Infrared

KC(s) – Key Characteristic(s)

KPI – Key Performance Indicators

LCA - Life Cycle Assessment

LCM - Low Carbon Manufacturing

NPD - New Product Development

PC - Personal Computer

PCB - Printed Circuit Board

PRISMA - Preferred Reporting Items for Systematic Reviews and Meta-analyses

PV - Photovoltaic

QFD - Quality Function Deployment

RF – Radio Frequency

RMS - Root Mean Square

ROI – Return on Investment

SHF - Super High Frequency

STEG - Solar TEG

TE - Thermoelectric

TEG – Thermoelectric Generator

UHF - Ultra High Frequency

UV - Ultraviolet

VHF - Very High Frequency

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1. INTRODUCTION

1.1 Thesis overview & background

Processes within the manufacturing industry are typically energy intensive and accounted for over one-third of global energy usage in the last decade (IEA, 2023). Data collated within the last decade also highlights that not only is our primary energy source (over 80%) fossil fuels, but the trend has also been on the rise too, burning more fuel each year from 116,214 to 136,761 terawatt-hours (TWh) within the last decade (Vaclav Smil,2017). Global greenhouse gas in the same period amounted to 49.4 billion tonnes carbon dioxide equivalents [CO2eq]. It is inevitable that demand for manufactured products is likely to increase in the years to come; Allwood et al. suggest 100% or more increase by 2050 (Allwood et al., 2011). A calculation by the International Energy Agency (IEA) finds that a reduction of direct emissions from industry of at least 24% (compared to 2007 figures) must be targeted to achieve the halving of overall CO2 emissions by 2050. (IEA, 2010). This recommendation owed to the findings of the United Nation International panel on climate change (IPCC), publishing that in order to confine further rise in global mean temperature to below 2°C and mitigate the possibility of further dangerous climate change effects (IPCC, 2007).

The IEA further identifies that if energy efficiency is made a priority (as per their Efficient World Scenario), energy savings of 25% within the transport sector and 14% in the industrial sector are possible, in comparison to New Policy Scenario (IEA, 2018). This thesis looks to consider a holistic approach through the Design for X paradigm – for this, one needs to fully understand the thought process to the DFX architecture to problem solving.

Design is central to engineering, creativity, and innovation (Eger et al., 2012, p1). Manufacturing typically revolves around a design specification, which stems from customer needs (CN). A successful design can further break down these customer needs to design parameters (DP) to allow the engineer to converge efforts on achieving the best result.

The design and manufacturing process generally follows a path of distinct, successive phases, with the design specification being narrowed in focus over time as the details are refined – as depicted pictorially in Fig 1.1 (visual concept presented in Thorne 2017).

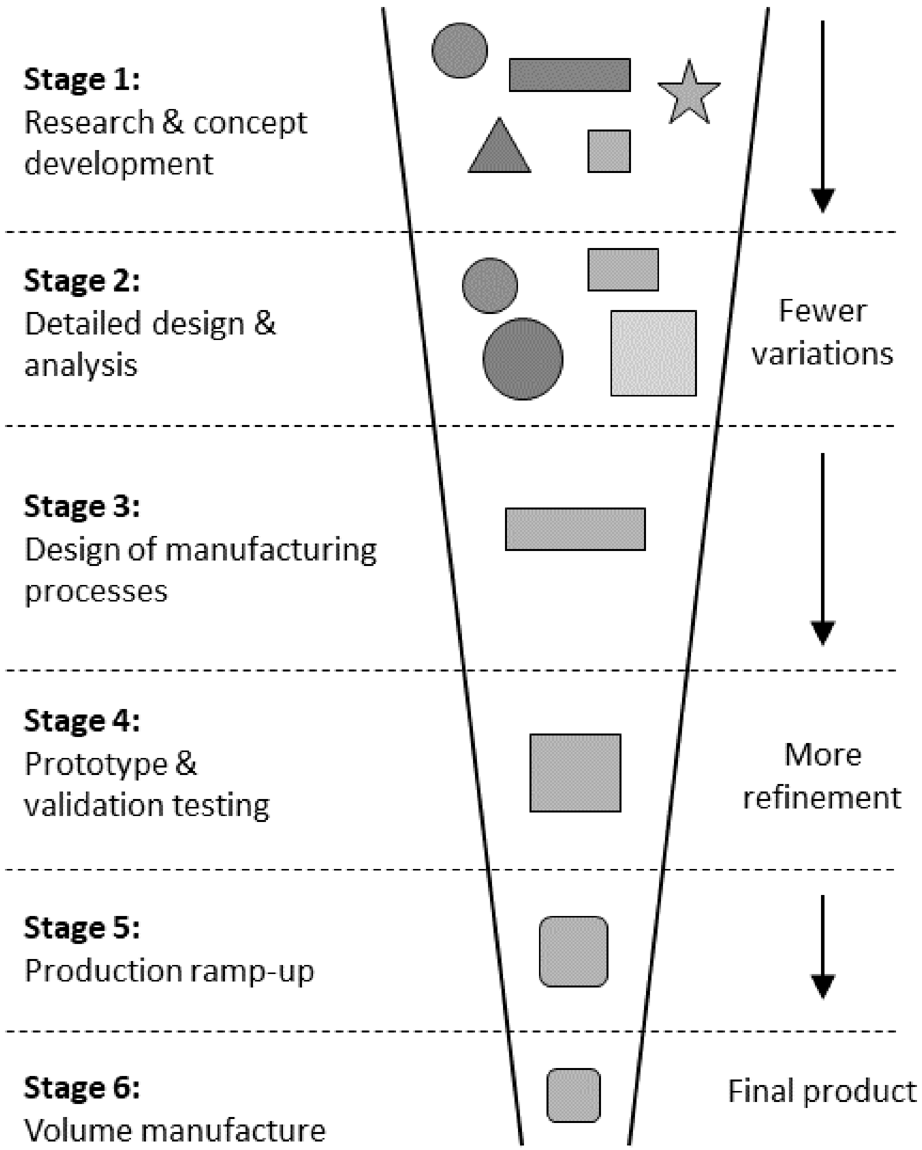

Figure 1.1 - Stages of design and manufacture

While Fig 1.1 is condensed to include actual production phases, the design phases 1-3 can be further broken down. Although there is no standardised list of design phases, there are commonly used phrases that describe those various aspects of the design process, some of which are summarised in

Table 1.1 - Description of design stages (Adapted from Haik and Shahin, 2010, p9, Mital et al., 2014, p22, Farag, 2018).

Table 1.1 - Description of design stages

Design stage	Description	Source(s)
Early ↓ ↓ ↓ Later	Problem recognition, market research, feasibility studies	(Haik and Shahin, 2010, p9), (Mital et al., 2014, p22), (Farag, 2018)
	Background engineering research	(Haik and Shahin, 2010, p9)
	Conceptual design, idea generation/synthesis	(Haik and Shahin, 2010, p9), (Mital et al., 2014, p22)
	Selection of concept/configuration	(Haik and Shahin, 2010, p9)
	System-level Design, Detailed Design, Selection of materials	(Haik and Shahin, 2010, p9), (Mital et al., 2014, p22), (Farag, 2018)
	Analysis and testing	(Haik and Shahin, 2010, p9), (Farag, 2018)

Every design stage serves as a platform to both communicate and share project information as well as provide necessary feedback whilst checking for inaccuracies as well as other types of conflicts present (East, 1998).

The conceptual stage of design is also referred to as the ‘early phase of design’. For products, this phase of the design process typically begins with an initial CAD model, typically created by a single user which is subsequently used to perform analyses for refinement (Elgueder J., 2011). This process is also applicable to design ‘process’ implementation, thus typically still an iterative process.

In addition, this stage will also see the proposed design validated against factors such as expectations by the customer and their satisfaction. These expectations play a critical role in increasing the eventual success of the product in the marketplace (Maropoulos and Ceglarek, 2010; Kortler, et al., 2012).

Engineering teams make use of design reviews to identify flaws or shortcomings in conceptual designs. Agents or stakeholders from multiple departments (including manufacturing) are brought together to ensure that the goals of each department are considered in the development process and that the design is validated from as many disciplinary angles as possible. Specific interest in this research is the importance of carbon reduction (towards a net zero emission strategy) – as discussed above. The significance of incorporating this into the design phases is discussed below.

Early design phases typically begin by identifying the constraints on the design, followed by a creative stage in which new solutions to the design problem are proposed. Conceptual creations usually then go through an iterative process to reach a formal manufacturing specification (BSI, 2015). The constraints that designers must consider in the early design phases cover many disciplines - from the obvious such as consumer desires or requirements, to the more arcane such as regulatory restrictions and environmental impacts.

Mascle and Zhao (2008) suggests that this phase in particular is also a very high determinant of competitiveness in industry, because according to them, up to 80% of costs involved in development (of product), product manufacture and use (of product) are typically determined at the initial design stages (Mascle and Zhao, 2008). A visualisation of costs committed at varied stages of the development process is depicted in Figure 1.2 (adapted from Garret, 2018).

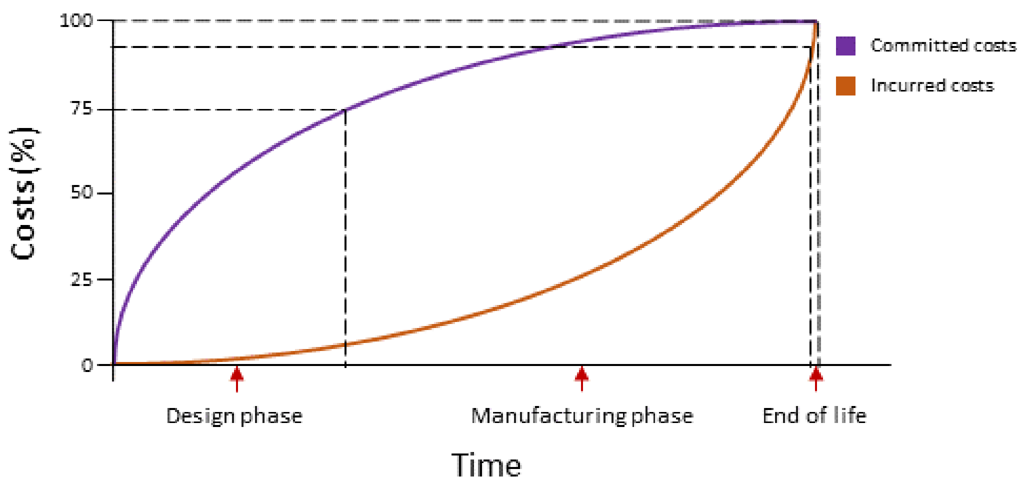

Figure 1.2 - Costs committed over a typical development cycle

Kiran (2017) emphasised the importance of full understanding of the early design phases, as it is necessary to facilitate design for quality (DFQ) based on its ability to provide:

“*a systematic overview of manufacturing through the concepts and tools emphasizing the role of quality in the total production cycle, including customer inputs, competitive benchmarking, and product and process design*”. – (Kiran, 2017)

There is also a growing view that DFQ should be incorporated into the findings of design science in addition to other existing methods, techniques, and philosophies - including design for assembly, design for quality functions and design for deployment (DFD) amongst others (Andersson, 1994).

Zhang et al. (1996) noted that manufacturing enterprises seek to optimise their production strategies owing to an increase in demand for “*better quality products with shorter lead times and lower life-cycle cost*”.

This cannot be accomplished economically, by internal improvements alone, but must also take into considerations a plethora of external factors including geopolitical ones. As it is near impossible to account for every existing factor to be considered, using validated information/guidance to create a holistic approach of dealing with the problem may be the most efficient approach towards achieving a lasting solution. It is therefore imperative that any solution being proposed is guided by validated data/science.

According to Zheng et al (2020), it is significantly more difficult to achieve net-zero within the industrial/manufacturing sector due to higher energy demands and shorter economic deadlines. This makes it one of the most challenging sectors in which to pursue this goal.

It must be said that even though most concepts and surrounding research within this area are not new, best practices are not deeply refined and in most cases are not holistic or longsighted enough to yield any meaningful operational results despite their identifying it as a key priority within their development/policy. As such, there is significant scope for research to identify the most significant implementation issues and barriers towards a net zero manufacturing strategy, and to propose a lasting solution to this problem.

This thesis consolidates and prioritises various solutions or approaches to dealing with the most commonly identified carbon reduction challenges in the implementation of manufacturing – in this case, due to manufacturing of tangible products being the scope of the general work, heavy industry and other forms of manufacturing including are left out of scope and this works consideration is thus limited to batch manufacturing.

A novel approach of energy recuperation is also considered towards the introduction and implementation of the next industrial revolution.

1.2 Contribution to knowledge

A systematic review conducted in the field of batch manufacturing reveals a notable scarcity of research focusing on this aspect of manufacturing and its contribution to greenhouse gas emissions, particularly CO2 (Seuring and Müller, 2008). It is undeniable that a substantial fraction of goods and machinery depend on this mode of production. However, due to the lack of stringent regulations, organisations are left to independently determine their interpretation of 'carbon neutral' (Awanthi and Navaratne, 2018). As a result, these definitions tend to vary between companies, leading to inconsistencies in measuring and reporting emissions.

For example, one firm may solely consider CO2 emissions in their definition, neglecting other greenhouse gases and their impact. This juxtaposition embodies a strategic alignment with the principal research questions posed in this thesis, ensuring a coherent and impactful contribution to extant scholarly discourse and practice in the field.

The recommendations presented aim to provide guidance towards a unified definition and identification of qualifying metrics, allowing for a more precise capture of relevant Key Performance Indicators (KPIs) for achieving net-zero emissions within this sector (Searcy, 2012). By bridging these gaps in understanding and standardisation, this work sets the stage for a comprehensive contribution to knowledge in the realm of sustainable batch manufacturing.

This thesis contributes to the existing body of knowledge on sustainable manufacturing practices by through the following:

1.2.1 Refinement of Carbon Emission Metrics and Batch Manufacturing

The first contribution emerges from the exploration of varying interpretations of "carbon neutral" amongst organisations and the resultant inconsistencies in emission measurements and reporting (Awanthi and Navaratne, 2018). Herein, a novel contribution is made by proposing unified metrics that are tightly interwoven with the batch manufacturing processes. Recommendations derived from this research offer nuanced guidance towards synchronising definitions and metrics, which in turn facilitate a more precise encapsulation of Key Performance Indicators (KPIs) required for achieving net-zero emissions in batch manufacturing environments (Searcy, 2012).

1.2.2 Strategic Utilisation of RF and TEGs in Batch Manufacturing

Strategically, this thesis navigates through the utilisation of Radio Frequency (RF) and Thermo-Electric Generators (TEGs) in the domain of batch manufacturing, emphasising their potential as prolific resources for energy harvesting in such environments (Paradiso and Starner, 2005; Zhu et al., 2014). The research transcends mere exploration by probing into the constraints, such as limited energy generation, and offering innovative techniques for amplifying and storing harvested energy. This naturally dovetails with batch manufacturing where constant and consistent energy sources are pivotal, hence, contributing to reducing the carbon footprint of the sector by offsetting energy demands (Wang et al., 2016).

1.2.3 The Symbiosis of Upcycling and Batch Manufacturing

The work in the Thesis elucidates a detailed examination of upcycling within the batch manufacturing milieu, underscored by its potential to significantly mitigate waste and synergistically complement circular economy principles (Ghisellini et al., 2016; Lieder and Rashid, 2016). The nuanced integration of upcycling strategies, particularly within batch production processes, not only ensures material and energy efficiency but also fortifies environmental sustainability by minimising waste generation and enhancing resource utilisation.

1.2.4 Adoption of Modular Component Building in Batch Production

Significantly, this thesis intertwines the concept of modular component building within batch production, elucidating its propensity to enhance flexibility, adaptability, and efficiency in manufacturing processes. Notably, this approach allows for a more agile and responsive manufacturing process, which, when coupled with energy harvesting and upcycling, ensures a holistically sustainable and efficient production cycle, further mitigating the environmental impact of manufacturing practices.

1.2.5 Regional Adaptability and Customisation

Finally, the research brings forth a nuanced understanding that regional disparities necessitate customised approaches towards achieving sustainability within manufacturing sectors (Creutzig et al., 2018). Therefore, this thesis contributes by spotlighting the imperativeness of adopting regionally tailored strategies in harnessing locally available and excess resources, thereby aligning energy harvesting and upcycling practices with the specificities of regional manufacturing contexts, including batch production.

In summary, this research intricately braids the threads of batch manufacturing, energy harvesting (via RF and TEGs), upcycling strategies, and modular component building, offering a comprehensive, innovative, and practically applicable contribution to knowledge in sustainable manufacturing practices. By connecting these multidimensional facets, the thesis not only reinforces academic understanding but also pragmatically guides industry practitioners and policymakers towards the realisation of net-zero emissions within batch manufacturing, thereby symbiotically advancing both theory and practice in sustainable manufacturing.

1.3 Structure of this Thesis

This thesis is composed of carefully arranged sections that aim to present the reader with concise summaries of each pertinent research area. By structuring the work in this manner, a comprehensive understanding of the subject matter is presented, followed by the results of testing and conclusions regarding best practices.

Declaration statement – An attestation to the fact that the work presented is that of the author.

Abstract - A very short overview of the purpose and findings of this thesis

Acknowledgment - A note of appreciation to all those who have made this work to be done successfully.

Table of Content, Acronyms and List of figures – A content table to help the reader navigate the report and additional lists with definition including a comprehensive list of all the figures and tables within this thesis.

Introduction – A brief explanation of the context and fundamental backbone in which the project is set and relies upon.

Aim and objectives – Concise statements detailing the outcomes which are to be achieved, Background and related work – A review of the literature in the fields of (primarily) Net Zero Batch Manufacturing and Energy Scavenging (with tangential references to other related concepts)

Literature review – A more detailed examination of papers with significant influence towards the final proposal of Net Zero within batch manufacturing

Batch Manufacturing and Carbon footprint – This section of the thesis considers the findings from all literature reviewed and how it can be collated into a singularised approach towards achieving net zero within batch manufacturing. The integration of energy harvesting is also looked at within this part of the thesis. This is focused on harvesting energy within the manufacturing environment using antennas and TEGs. The findings from the research in these technologies are intended to inform best practice guidelines for manufacturers and policymakers.

Concluding remarks – Author's commentary on the findings and success of the project, with limitations noted and suggestions for future work provided.

1.4 Aim and objectives

1.4.1 Aim

The aim of this work is to explore energy harvesting strategies and upcycling in the manufacturing sector, with the ultimate goal of achieving net-zero emissions. The research draws upon the Design for X (DFX) paradigm, which encompasses various design considerations to improve product quality while reducing environmental impact.

The aim of this thesis is to explore and assess innovative energy harvesting strategies and upcycling practices within the manufacturing sector, particularly focusing on their potential to contribute towards achieving net-zero emissions. Grounded in the Design for X (DFX) paradigm, this research extends beyond traditional design considerations, emphasising environmental sustainability and efficiency to enhance product quality and reduce environmental impact.

Building on the foundations laid in the initial chapters, particularly the strategic utilisation of RF and TEGs in batch manufacturing (section 1.2.2) and the symbiosis of upcycling with batch manufacturing (section 1.2.3), this thesis delves into the feasibility of harnessing energy harvesting technologies. Specifically, it examines the use of Radio Frequency (RF) and Thermoelectric Generators (TEGs) to convert waste heat and electromagnetic radiation, routinely emitted by industrial equipment during the manufacturing process, into usable electricity.

This approach directly contributes to reducing energy consumption and emissions in the manufacturing process in several ways:

Efficient Energy Utilisation: By converting waste energy sources, such as heat and electromagnetic radiation, into electricity, the need for external energy inputs is significantly reduced. This aligns with the principles of DFX, which advocate for efficient use of resources.

Reduction in Carbon Footprint: The generation of electricity through RF and TEG technologies reduces reliance on conventional, often carbon-intensive, energy sources. This is a practical application of the refinement of carbon emission metrics in batch manufacturing, as discussed in section 1.2.1.

Enhancing Upcycling Practices: The integration of these energy harvesting technologies complements the upcycling strategies explored in section 1.2.3. It adds a new dimension to upcycling by not only reusing materials but also by capturing and repurposing energy waste.

Modular Component Building: The adoption of modular component building in batch production (section 1.2.4) can be further optimised by integrating energy harvesting technologies, thus enhancing energy efficiency and reducing emissions.

Regional Customisation: With the regional adaptability and customisation discussed in section 1.2.5, the application of RF and TEG technologies can be tailored to specific industrial setups and regional characteristics, optimising their effectiveness in reducing energy consumption and emissions.

By investigating the feasibility of using these technologies, this study aims to contribute to the development of sustainable manufacturing practices through upcycling, where, by inference, the waste heat and RF being converted to usable energy can be considered as an upcycling practice in itself.

The methodology will be through Design for Excellence (DFX) architecture. Application of energy harvesting considerations supporting the design outcome improvement process with existing knowledge relating to carbon reduction strategies will also be considered.

In the Design for “X” paradigm ‘X’ is a variable representing for various aspect or objectives being considered for design optimisation, specifically to achieve better design

(Ukala et al., 2020) through an increase in designer awareness to the characteristic that is depicted by “X” (Kuo et al., 2001). “X” can be representative of several traits or features including reliability, yield, variability, cost, power, or manufacturability (Mohanty, 2015), where ‘X’ in this case is considered to be ‘Net Zero Carbon Manufacturing’.

Exploring the concept of upcycling and investigating its viability in the manufacturing process. The case considering of effectiveness of upcycling in reducing waste and making a positive contribution to a circular economy. By exploring the concept of upcycling, this thesis aims to provide new insights into sustainable manufacturing practices.

Ultimately, this research aims to contribute to the growing body of knowledge on sustainable manufacturing practices and provide valuable insights for policymakers, industry practitioners, and researchers seeking to achieve net-zero emissions. By investigating the feasibility of using energy harvesting technologies and proposing modular component build and upcycling as sustainable manufacturing practices, this thesis aims to provide new perspectives on sustainable manufacturing practices that can contribute to reducing waste and emissions in the manufacturing sector.

1.4.2 Objectives

The aim is hoped to be achieved through the following objectives:

O1) Conduct literature review on the current state of the art within carbon reducing strategies in batch manufacturing.

O2) Review batch product manufacturing processes together with current applicable carbon footprint and explore methods by which integration of energy harvesting to the manufacturing environment is devised to be integrated into a carbon reducing approach (including limitations).

O3) Following from objective 2, designing a novel approach for realisation of a standardised compliant manufacturing scenario within Design for X architecture. These best practice guidelines will access detailed product information that exist within integrated manufacturing environment and will explore methods within the current state-of-the-art, such that these parameters can be inputted, and dataset extrapolated to determine how carbon footprint can be reduced. The finality will be realising a prototype that will validate standard compliant method based on predetermined (experimental) requirements.

O4) From the results of the aforementioned objectives, propose a set of best practice guideline which may be systematically applied in industry settings to improve carbon footprint reduction within batch manufacturing and evaluating the prototype through testing.

2. LITERATURE REVIEW

This chapter considers and reviews available literature of notable material including published work and white paper within the areas of DFX Paradigm, Batch Manufacturing, ‘Net Zero’ manufacturing, and Energy Harvesting through Radio Frequency using antennas and TEGs. These areas will provide the foundation for exploration of Net Zero batch manufacturing processes.

2.1. The concept of achieving ‘Net Zero’ in manufacturing

2.1.1 Design for X (DFX)

Arguably, the most popular use of the DfX philosophy, as this confirms manufacturability of the product being considered – usually by referencing predefined design rules and guidelines set out during the early stages of product design.

Historically, manufacturing companies would operate with a method colloquially known as “over-the-wall”, meaning that concept designers would produce a design and pass it to manufacturing engineers to prepare the necessary manufacturing plans (Boothroyd, et al., 2002, p. 7) (Anderson, 2014, p. 4). With increasingly complex products and assemblies, this would naturally result in either excessive costs to manufacture a non-optimised design, or delays to modify elements, which were impractical or impossible to create with existing manufacturing methods.

It therefore became necessary to make considerations for manufacturability throughout the design process to reduce development time and manufacturing costs. Substantial effort has been made in moving DFMA and other DfX approaches earlier in the product development cycle to help achieve these goals – it is commonly cited that over 70% of final product costs are determined in the design phase (Boothroyd, et al., 2002, p. 5).

Manufacturability is the ability to reproduce a given part with minimal waste, such that it satisfies the requirements in intended use, while meeting the business goal (Rao, 1994). Typically, industrial design is associated with influencing aspects such as product appearance, ergonomics, and user interface (Campbell, et al., 2003). However, product design is more closely associated with the product being able to meet technical functionality and manufacturability as predetermined by the designers in the concept stage. Previously, a failure to communicate at key stages and the ignorance of some industrial Designers about topics they considered to be outside their own particular field led to frictions and inefficiencies in the new product development (NPD) process (Boothroyd, et al., 2001).

In Kaebemick, et al. (2003), the authors provide a simplified Life Cycle Assessment (LCA) for product development engineers to evaluate environmental impact of a product in the early design phases when detailed information about the product and manufacturing processes are not yet available.

A framework for predicting end-of-life of costs at the concept design stage is proposed by Cheung, et al. (2015). The methodology makes calculations for each of several different end-of-life options (such as refurbishment or recycling); however, the authors note that further development of this approach is required to account for factors such as disassembly time of an end-of-life product.

Current day complexities in the supply and demand chain process as well as the need for new and updated products by consumer and industry alike means that the manufacturing industry is constantly turning to the use of simulation models. According to Maropoulos, and Ceglarek (2010), in order to successfully compete in the global market:

"*Manufacturing companies are increasingly expanding simulation models from product and process based (value chains) to service based (value networks) by focusing on lifecycle simulations and design for product variation*" (Maropoulos, and Ceglarek 2010). This allows them to produce efficiently whilst minimising wastage.

A popular method of evaluating customer requirements is through Quality Function Deployment (QFD), a set of tools designed to aid in identifying the most important factors for consideration and subsequently "deploy" them to the relevant department within the organisation (ASQ, 2018).

During the early stages of product design, a lot of emphasis is placed on particular existing data such as lifecycle requirements, technical requirements, and manufacturing requirements. These requirements are usually derived from the correct understanding and subsequent interpretation of market needs – because the whole idea of a new product ultimately relies on the product or service being profitable to the manufacturer.

Validity checks of a new product play a vital role at the early stages of product design as has been referenced severally in earlier sections of this thesis. This section of the thesis considers both the technical aspect of the process that ensures design consistency – in-line with maintaining key design objectives through the use of Key Characteristics (KCs) and DFX methods, as well as the methods utilised for quality function deployment (QFD) and validation of design ideas.

The method to validating a new (or revised) product needs to be defined clearly, with records kept showing these and subsequently approved in advance prior to starting a design activity.

<u>Manufacturing considerations</u>

Key considerations typically acknowledged at the early stages of design are:

- Prioritisation of customer needs (this should be done quantitatively according to market analysis).
- Selection of the best design.
- Communication improvement (with respect to all key stakeholders).

Matrix prioritisations, as well as analytical hierarchy processes (Ramanathan and Yunfeng, 2009), are frequently applied to allow the enterprise to determine optimum resource usage for maximised returns.

Traditionally, analysis of CNs is systematic as this allows these needs to be translated into relevant product features. This can be difficult as the assessment of performance can be tricky to achieve in a quantitative evaluation process. Research done by Büyüközkan et al. (2004) presents an approach that allows improved alignment of CNs with objectives of the development of the product with the use of QFD The prioritisation of CNs produces criteria which is used to validate the final product, this process allows the assessment of the product to confirm that the right product, process or system is affected.

QFD is typically customer driven. The implementation to product design and development systematically underpins the overall quality of the product being designed or built and has been extensively used in various industries for product development. This is because it allows further developments of various tools and systems that assist an enterprise with the understanding of customer feedback (Ramanathan and Yunfeng, 2009).

In summary, it can be said that QFD ultimately has the ability to convert CNs into tangible design requirement or parts deployment (Shimomura et al., 2008).

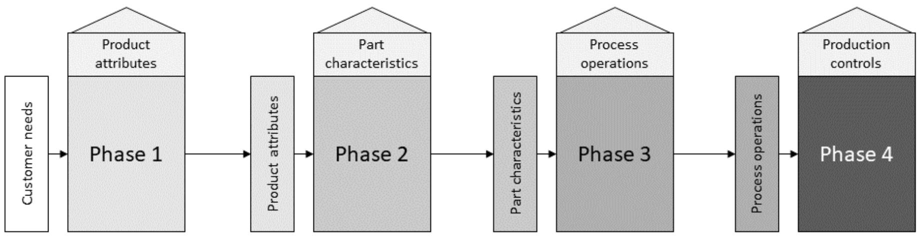

Figure 2.1 - Four-phase process planning by QFD

Figure 2.1 shows a typical QFD table (as presented by Chen and Ko, 2009), which is made up of four phases with the intention of transcribing customer feedback to product design requirements as shown in phase 1. This is further translated into characteristics for the parts as shown in phase 2, followed by subsequent manufacturing operations, which are analysed in phase 3. This effectively allows the final phase (phase 4) to be achieved.

The Df(X) paradigm is utilised later in this thesis with respect to energy harvesting and best practices thereof, which can be incorporated into earlier design phases and manufacturability considerations for optimising energy usage.

2.1.2 Key Characteristics (KCs)

Key Characteristics or KCs refer to the process of identifying and analysing the attributes that need to be controlled, which are of much significance in the development of complex product or processes and in ensuring quality thereof the product. Any deviations from the expected quality of the product characteristics such as unambiguity in the resulting attributes, decline in performance or those in the targeted outcomes leads to loss in terms of additional cost overhead.

"*KC methods are most successful if implemented in the early stages of the design phase because this can increase the capacity to efficiently treat the product/ process robustness*" (Almeslemi et al., 2018)

Major companies for example Boeing, Ford and Xerox now proactively use KCs in their product design and manufacturing process. There are two approaches on when to identify the KCs – proactive and reactive approaches.

- In the proactive approach, the factors or variations that are likely to hinder the product or process performance and quality are found during the early phases of design. This process of identification of such factors is usually done by collecting requirements and having consecutive discussions with the customer, the product end users, the design team, implementation team and finally the testers. This approach leads to robust product development.
- In the reactive approach, the need for identifying the KCs arises at the time of the production issue – usually during manufacturing or testing.

When comparing both the approaches though they use qualitative identification process, proactive seems to incur less probability of negativity in production process, since all the likely occurrences of pros and cons have been analysed and appropriate measures have been taken to solve them. While the reactive, results in cost overhead of producing low quality product and the time and effort required for solving the problem.

Table 2.1 describes various aspects of KC.

A major disadvantage with the reactive mode is that easily avoidable costs are incurred (Thornton, 1997) - an example is the production of lower quality parts that is only identified during inspection and may need to be reproduced and re-inspected.

Table 2.1 - Identification process of Key Characteristics

KC	Implementation Perspective
What is KC?	Properties/parameters/attributes of product/process/system/part
KC Identification	Proactive Identification- The KCs are identified during the early development phase of said product.
	Reactive Identification- Here the KCs are usually identified during the late stages of manufacturing and while testing.
How to identify KC	By means of Analytical and Statistical models
Significance	The organisational factors such as customer satisfaction index, cost, quality, and performance rely on the accuracy of these factors

With KCs in place, there are higher chances of issues to exist during the manufacturing stage when too many KCs have been identified. As a solution to this issue, a hierarchical or top-down approach is used, which decomposes the whole product/process into lower levels of assembly and product KCs (Mathieu and Marguet, 2001).

Figure 2.2 (adapted from ideas presented by Zheng et al., 2008) shows how the KCs are broken down into the 4 levels, namely:

- Product level KC,
- Subsystem level KC,
- Part level KC, and
- Process level KC

This split is introduced to ensure that the variations are identified and corrected at each level of the product-manufacturing phase resulting in the creation of a robust product.

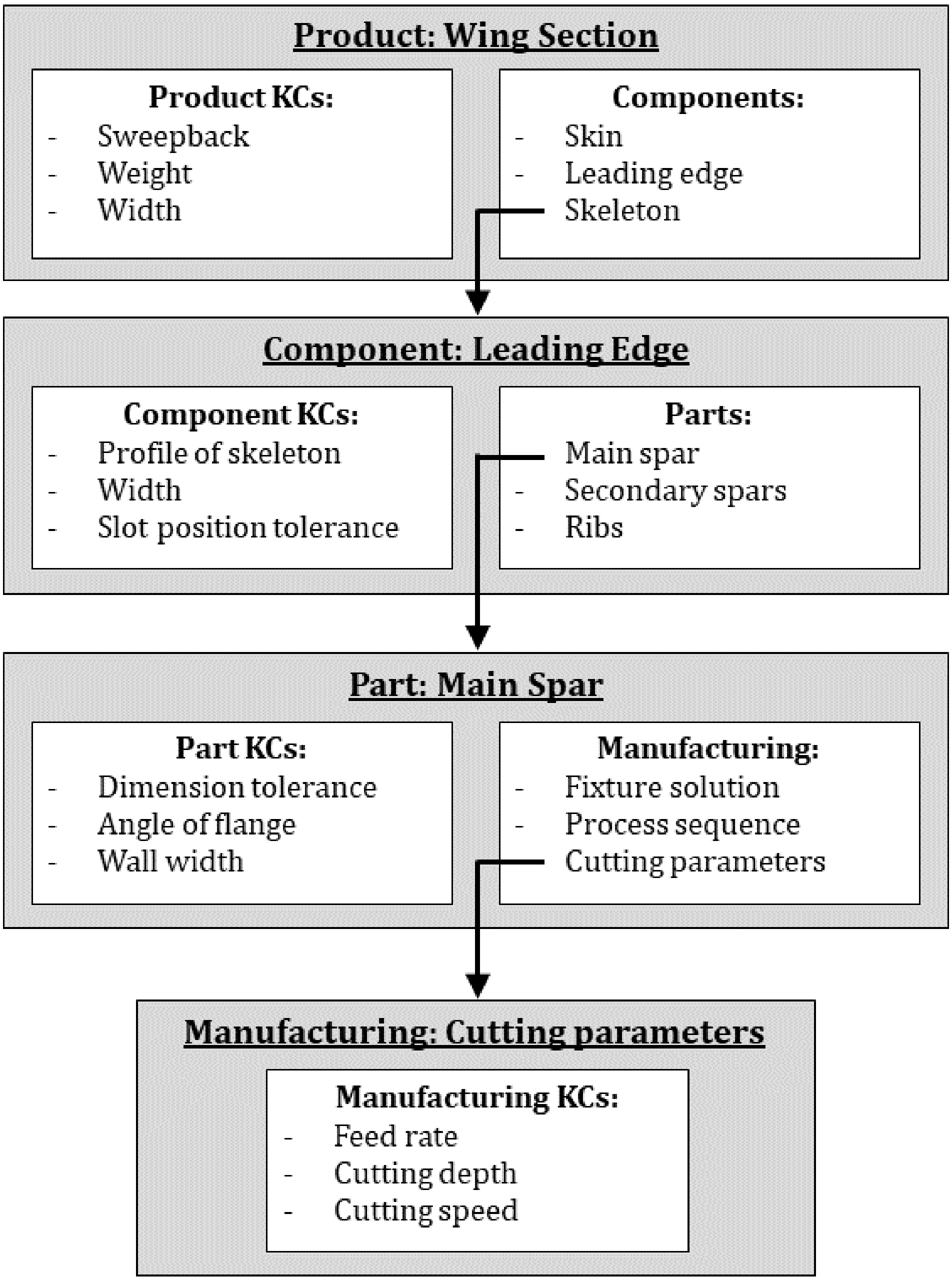

Figure 2.2 - Key Characteristic flowdown

2.1.3 Justification for 'Batch Manufacturing' Consideration

Batch manufacturing is a widely used production process utilised in various industries. It involves the production of a specific number of products within a defined period, making it suitable for situations where a specific product requires a certain amount of customisation or variation. In this section, the justification for the selection of batch manufacturing, focusing on cost, waste reduction, and ease of assessing GHG emissions will be discussed. Cost is usually a significant factor in selecting batch manufacturing. Batch production allows for better control of material and labour costs as the production of a specific number of products means that there is less waste and more efficient use of resources. In comparison to continuous or assembly-line production, batch production is more flexible in meeting customer demands, which can help to reduce the risk of overproduction and unsold inventory, leading to significant cost savings. This is supported by studies such as Gilbert and Emmons (1995), AlDurgam et al. (2017), Virtanen et al, (2022), and Benkherouf et al. (2017) which highlight the importance of cost management in batch production.

In terms of waste, even though the batch manufacturing process runs more efficiently that most other methods, waste reduction is still a key factor in selecting batch manufacturing. Batch production allows for greater control over the amount of waste generated in the production process. By producing products in smaller quantities, businesses can reduce the risk of overproduction and unsold inventory, which usually lead to waste. Additionally, batch production allows for greater control over the use of materials, which can help to reduce waste in the production process. Several studies have examined the relationship between batch manufacturing and waste reduction, including Ghazi-Nezami and Heydar (2018), Dwivedi et al, 2023, and Li and Chen, 2023).

Finally, one of the key reasons for the use (and consideration within this thesis) of this type of manufacturing is ease of access and ability to replicate a typical manufacturing factory setup compared to large-scale mass production, thus allowing useful data collection of GHG emissions in a similar manufacturing environment. Moreover, batch production is often seen as more environmentally friendly than continuous or assembly-line production, as it allows for greater control over the use of materials and energy. This makes it easier for businesses to assess and reduce their GHG emissions, as they can more easily track the use of resources and identify areas where improvements can be made. Several studies have examined the impact of batch production on GHG emissions, including Priarone et al. (2016), Xia et al. (2015), and Mejía-Moncayo et al. (2023).

In conclusion, the selection of batch manufacturing over other production processes can be justified based on cost, waste reduction, and ease of assessing GHG emissions. Batch production allows for better control of material and labour costs, reduces waste, and makes it easier for businesses to assess and reduce their environmental impact. Therefore, it is a suitable production process for businesses that require flexibility in meeting customer demands while minimising costs and environmental impact. These qualities also make it ideal for the validation of experimental data as is required for this thesis.

2.1.4 Greenhouse Gas Emissions in Manufacturing

Batch production is regarded as the method of manufacturing where groups of similar products are developed simultaneously. The manufacturer is typically responsible in deciding the size of the batch and implicitly how these batches would be developed. Each of these batches thus go through individual stages of the manufacturing process

(Gilbert & Emmons, 1995). According to Benkherouf, Skouri and Konstantaras (2017), there exist several different approaches which can be undertaken by the manufacturer when considering the production processes. The flexibility of batch manufacturing processes means that it is typically favoured within the manufacturing sector.

The industry of manufacturing asserts significant duty for greenhouse gas emissions. For instance, the industry of manufacturing accounts for 23% of the carbon emission as per the Environmental Protection Agency (Burton, 2020), which only considers the direct emissions (Tian et al. 2018). According to the research of Li and Cheng (2020), the industry of manufacturing is recognised as one of the potential contributors to greenhouse gas across the globe. These figures thereby make the manufacturing industry the largest contributor after transportation and electricity. The primary greenhouse gas emissions originate from heating and electricity usage, while others include manufacturing, forestry and transportation. The carbon emission across the manufacturing also occurs due to the chemical reactions which occur amidst steel, iron, cement, and other chemical production (Liu, 2022).

The notion of green manufacturing is widely described as the effort to lower the environmental influence of human activities and to create a competitive and resource-efficient economy (Paul, Bhole, and Chaudhari, 2014). This is also generally done by adhering to the action plan, which aims toward better utilisation of resources under the carbon neutrality circularity and biodiversity restoration (Abualfaraa et al. 2020). On the other hand, carbon neutrality largely refers to reducing the emission of carbon to zero – with current goal set at the year 2050. According to Karuppiah et al. (2020), green manufacturing does not just mean investing in technologies which are environmentally sustainable – it also aims to support innovative solutions across the industry, cross-sectoral collaboration and decarbonisation. Green manufacturing is also aimed toward utilising the resources in a closed loop for minimising the carbon footprint and pollution alongside addressing the leakage with the help of economic growth (Leong et al. 2019). Similarly, the transition towards the circular economy includes the execution of a systematic approach as well as policies across the regional level. As per the literature of Stavropoulos et al. (2022), there exist certain digital techniques which support the meta-modelling of technology, including industrial symbiosis, life cycle analysis, business model evaluation and circularity performance assessment.

2.1.5 Low Carbon Operation (and towards net zero)

The threat of global warming is providing impetus to substantial innovations in material design to enhance energy production, techniques of energy harvesting, reducing energy consumption, and increasing energy efficiency in industrial and domestic purposes (Villacreses et al., 2017). In spite of the assertion that there is a concerted global effort to reduce fossil fuel dependency, crude oil consumption surged from 95 million barrels in 2014 reaching around 100 million barrels in 2018, translating in up to 5.5 million barrel per day (Jaziri et al., 2020). Within a similar period, electricity cost has also continuously increased - partly due to socioeconomic and political factors, further aggravated by depleting fossil fuel supply. A gradual transition towards carbon-free renewable energy sources seems to be imminent. Although it is arguable that all other viable options have been explored and given the same number of resources and commitment to test – the reasons for this transcend practicality or availability of resources and sometimes are purely political or even regional.

The process of producing low-carbon items using environmentally friendly manufacturing techniques that use less energy and emit less carbon dioxide is referred to as low-carbon manufacturing (LCM). In contrast, sustainable production places an emphasis on reducing both the consumption of resources and the negative effects on the environment. The studies of the relevant literature can draw the conclusion that manufacturing with low carbon emissions is a method that is all-encompassing, well-rounded, and beneficial. This process involves a lot of different variables, such as the design of the product, different management styles, different manufacturing techniques, different production tools, and individual quality. According to Zheng et al (2020), it is significantly more difficult to achieve net-zero energy in the industrial sector due to higher energy demands and shorter economic deadlines. This makes it one of the most challenging sectors in which to pursue this goal. It is challenging for the machinery manufacturing business to successfully embrace low-carbon manufacturing because of the one-of-a-kind nature of equipment goods and the complexity of low-carbon production. This presents a challenge for the industry that is responsible for creating machines (Groza, Nadot, and Varadi, 2018).

This industry produces finished commodities through the utilisation of mechanical power. The production of metal, for example, is often accomplished by processes such as forging, stamping, welding, shaping, machining, and assembly (Smith et al., 2013), relying on electricity for the majority of the energy that it consumes, which is a discrete production system. Because of this, the industry is considered to have a lower overall energy consumption level. Lu, Zhang and Zhou (2023) presents a four-layered system architecture for low-carbon operating models in the machinery manufacturing business. The results of previous research as well as the lessons learned during the process of adopting low-carbon manufacturing went into the creation of this framework. According to Wang et al (2021), it is possible to deduce that low-carbon manufacturing places an emphasis on boosting energy utilisation ratio and resource utilisation ratio by utilising low-carbon product design, low-carbon energy structures, low-carbon manufacturing processes, and low-carbon product disposal. These are the factors that contribute to low-carbon manufacturing.

Initially, the manufacturing of machinery employs a technique that reduces carbon emissions during the production process. Economic and societal benefits are maximised by production that does not emit carbon dioxide. The objective function incorporates variables relating to the economy and society (Groza, Nadot, and Varadi, 2018). The establishment of a paradigm for sustainable development that takes into consideration resource and energy consumption in addition to carbon emissions is finally possible.

To reduce the quantity of carbon emissions created during the manufacturing of machines, four strategies can be implemented: low-carbon product design, source control, process control, and end-of-life product disposal. Developing products with a small carbon footprint leads to the construction of energy- and resource-efficient items. Source management is the process of finding sources of low-carbon energy and raw materials with lowest environmental impact. To reduce the quantity of carbon emissions produced by a process, energy and material savings are taken into account. Utilising, remanufacturing, or recycling objects whose useful life have expired (Watari et al., 2021; Mejía-Moncayo et al., 2023).

The acquisition of raw materials, production, usage of the product, and finally disposal of the item at the end of its useful life are the stages that comprise the life cycle of a product. It's possible that machines will need more energy when they're running than they did when they were being built. The production of low-carbon commodities ought to incorporate both the development of and the utilisation of machinery (Groza, Nadot, and Varadi, 2018). In order to achieve low-carbon production in the machinery business, there needs to be a reduction in carbon emissions across the product's whole life cycle. The construction of a carbon emission monitoring and control system, a low-carbon design system, an energy information gathering system, an energy optimisation system, a low-carbon management information system, and a low-carbon design system are all components of the machinery manufacturing business (Jeon, Kim, and Yang, 2022).

In order to successfully implement low-carbon manufacturing, it is necessary to first determine its strategic objectives and driving drivers. The primary goal of the equipment industry is to achieve low-carbon production at the first layer (Trivyza, Rentizelas and Theotokatos, 2018).

There exist several ways through which carbon emissions can be lowered. Such that there exist technologies which have been represented by the EU commission. Moreover, scrap recycling is considered a circular economy in action, and electrification is used for electrolysis in order to reduce the footprints of carbon (Tsai and Lu, 2018). There also exists the option of carbon storage or using alternative sources of power, including biomass or hydrogen. As per Tayyab et al. (2020), there exist different measures which can lower the emission of the manufacturing sector by about 75%. Such that the roadmap is largely commissioned through the industry of steel, whose restrictions range from 10 to 36 per cent (Hollanders, Es-Sadki and Merkelbach, 2019). It would be fair assumption to consider that the implementation of these or similar technologies if adopted, could reduce GHG in the batch manufacturing sector.

2.1.6 Metrics behind the theory

Various mathematical models are available to calculate the reduction/generation of GHG. The most commonly used ones tailored towards calculating carbon reduction in manufacturing are considered in this thesis. It is important to note that the specific model to be used depends on the context, data availability, and the objectives of the study.

- Life Cycle Assessment (LCA) - This is a tool used to measure the environmental impact of a product or service over its entire life cycle, from raw material extraction to disposal.

- Input-Output Analysis (IOA) - This is a technique used to model the interdependence of various sectors of an economy, allowing for the assessment of the carbon emissions impact of a particular sector.

- Linear Programming (LP) - This is a mathematical optimisation model used to determine the most efficient allocation of resources, including energy and materials, to minimise carbon emissions in manufacturing processes.

- Process Simulation - This is a computer-based model used to simulate and optimise manufacturing processes, taking into account energy usage, material flow, and other factors that contribute to carbon emissions.

- Carbon Footprint Analysis - This is a method used to quantify the amount of carbon dioxide and other greenhouse gases emitted as a result of a particular product or process.

- Dynamic Energy Assessment (DEA) - This is a method used to analyse the energy usage and carbon emissions of a manufacturing plant over time, taking into account changes in production levels, technology, and other factors.

- Circular Economy Models - These models aim to promote the use of resources in a more sustainable way, reducing waste and emissions, by optimizing the use of materials, energy, and other inputs in a closed-loop system.

As the above models consider GHG metrics (of which carbon footprints are one example), it is necessary to select one that is by consensus an accurate tool, as well as being able to be used in the quantification and qualification of laboratory case studies carried out within the works of this thesis. This results in further scrutinising the aforementioned models in order to choose one where relevant metrics from test/case studies within this thesis can prove useful in proofing and providing quantifiable and fairly accurate metrics of the merits of adopting the methods being proposed within this work.

By consensus (Rebitzer, et al., 2004; Lenzen, 2000; Hoekstra and Van den Bergh, 2006; Su et al., 2010; Geissdoerfer et al., 2017; Kirchherr, Reike and Hekkert, 2017), three highly reliable mathematical models for calculating carbon reduction are with the use of Life Cycle Assessment (LCA), Input-Output Analysis (IOA) and Circular Economy Models.

2.1.7 Policy and market solutions to carbon targets

In 2020, the current net territorial GHG emission in the UK was around 405 million tonnes. (Department for Business, Energy & Industrial Strategy, 2022). Jimenez (2022) surveyed global data in which 43% of respondents said that pharmaceutical sector batch manufacturing is pressing the environment and also increasing the rate of carbon emission. Jimenez (2022) stated that at every step of the manufacturing of pharmaceutical products, oil products produce a carbon footprint. To meet ambitious net zero targets and to reduce the carbon reduction in manufacturing several corporations, such as the automotive, and pharmaceutical amongst other sectors have adopted the framework of carbon credits. The process of carbon credits in its current operating form was conceived at the 1997 United Nations' Intergovernmental Panel on Climate Change (UNIPCC) in Kyoto, an agreement later termed the 'Kyoto Protocol' was reached to set carbon emissions for all participating countries in a bid to reduce emissions globally (UNFCCC, 2023).

At the meeting, the mechanism now typically referred to as 'Carbon Credits' or Certified Emission Reduction (CER) was devised with the goal being to allow a company the ability to purchase sufficient Carbon Credits, thus allowing it to continue emitting greenhouse gases up to an upper set limit – this is necessary in heavy emitting industries such as steel manufacturing amongst others. Around 170 countries are currently signed up to the Kyoto Protocol and are allotted which is determined by their pollution levels. The CERs are policed through the regions nominated National Registry, where part of the body's duty is to set quotas for the emissions on polluting industries, companies or other organisations which is then fed back to the United Nations Framework Convention on Climate Change to be approved and subsequently monitored. In the United Kingdom, the EA (Environmental Agency) acts as that body to nationally administer, acting as the Registry and thus allocates distribution to the open market by auction.

If the company emits lower CO_2 than the allocated limit, they can trade the surplus Carbon Credits to a different company that might need them to reduce their own emissions. However, if they emit more gases than the limit they have been allocated, then a fine is imposed. The idea being that receipts of fines levied are then invested into other projects supporting ones that reduce/absorb pollution, such as planting trees which absorb CO_2. Over time these set limits are gradually reduced until such time that the company is able to achieves net zero, meaning that the process gradually removes as much GHG as they produce. Carbon markets have become a significant means of accountability to industries worldwide in mitigating the current climate crises (Lohmann, 2010).

With the net zero commitment rate being on the rise in recent times, over a hundred additional subscribers are also starting to adopt some of these proposals and focus on carbon reduction in a bid to achieve a net zero target (Climate Action 100+, 2022).

Unilever, a prominent global operating multinational corporation, well known for its diversified and environmental sustainability operations has made significant efforts (in line with guidance) to further reduce its carbon emission levels – it has benchmarked its 2008 levels (one of its highest levels) and undertook a commitment to continually reduce its GHG emission levels in the coming years (Unilever, 2022).

Shell Oil, a similar multinational conglomerate has also committed to making similar changes, including short-term goals of 2-3% by 2021, 2-4% by 2022, and 6-8% by 2023 (Shell.com, 2022). In 2020, it also includes intermediate and long-term goals of 20% by 2030, 45% by 2035, and 10% by 2050" (Shell.com, 2022). To fulfil its goal, Shell has opted to use the carbon credits system whilst integrating it to continually improve its manufacturing methods.

There are arguable limitations to the 'Carbon Credit' scheme, some have suggested that Carbon Credits don't actually reduce the emission of GHG, Critics argue that the utilisation of certificates for pollution reduction is counterproductive, as it merely relocates the polluting emissions to another party that is willing to purchase the certificates rather than investing in eco-friendlier practices. Moreover, they contend that the projects funded by the sale of such certificates often prioritize short-term objectives instead of long-term initiatives such as reforestation. These concerns highlight the need for more sustainable and effective solutions to tackle pollution. These claims certainly carry some weight, as due to the absence of an effective United Nations coordinated mandate or global agreement, these carbon trading platforms are tending towards a more fragmented and complex entity (Lövbrand & Stripple, 2012) thus minimising its efficacy. This lack of formal implementation results in markets being created at various levels (transnational, regional, national, and sub-national levels) by both governmental entities as well as private sector actors, but the reality is that neither of them is linked to the Kyoto Protocol that should be governing the practice (Newell, Pizer, & Raimi, 2013).

2.1.8 Low Carbon Energy Source

The use of energy in some form is necessary for the performance of every action. In order to continue and advance, each process that makes up the dynamic system of production needs energy including a wide variety of separate industrial processes, as well as logistical linkages (Pourjafari et al., 2022). Throughout the hierarchy of the energy flow passing – including loss, storage, release, and transformation, a portion of the energy that comes from outside the manufacturing system (like electricity, for example) is transferred to each associated link or subsystem of the manufacturing system. A significant chunk of this energy is utilised to keep the activities of each link or subsystem running well, while the remainder is used to finish the tasks that are associated with the production process. This takes place as a result of the flow of energy. Energy flow is the key factor responsible for carbon emissions (Trivyza, Rentizelas and Theotokatos, 2018). This is because of the fact that reducing carbon emissions while simultaneously increasing energy consumption is not possible unless the source of energy is changed. In order to generate output that results in less carbon emissions, it is necessary to make adjustments to the energy structure and make use of sources of energy that do not produce carbon, sources that can absorb carbon or as a final resort, sources that can at least reduce the amount of GHG emitted.

Changing the composition of an energy source in order to generate less carbon dioxide emissions is an example of energy structure modification. Consider, for instance, the amount of energy that China consumes relative to the rest of the world. The production of standard coal as a primary energy source in the globe reached 3.18 billion tonnes in 2011, placing it in first place. Included are 3.52 billion tonnes of raw coal, 270 million tonnes of refined oil, and 200 million tonnes of crude oil (Zheng, Lai, Chen, and Zheng, 2019). The energy structure of China, which is predominately comprised of coal and is accountable for a sizeable portion of the country's high emissions, has not been significantly improved, and the transformation of China's energy structure still faces an overwhelming number of obstacles. This is due to the fact that the burning of coal to generate electricity releases a greater amount of carbon dioxide into the atmosphere than the burning of natural gas or petroleum does. Natural gas, wind, and solar energy should be utilised in the industrial sector rather than coal and other energy sources that produce considerable amounts of carbon emissions (Lotzof, 2023).

2.1.9 Other Considerations

A less frequently discussed method of carbon reduction is energy harvesting. According to Timelli, Caliari, and Rakhmonov (2016), energy harvesting is the process by which energy that has been gathered is either used immediately or stored for future use via a variety of different methods. The use of conventional batteries is one of the primary examples of applications for energy collection (Mo, 2022). Energy harvesting works by capturing minute amounts of environmental energy that is dissipated or wasted in the form of heat, vibration, light etc. (Allen et al. (2016). This energy may be accumulated and continuous over time, and that these very small amounts of energy may end up being sufficient to power small electrical or electronic equipment that perform essential duties for humans and businesses (Schulze, Heidenreich, and Spieth, 2018). Despite this, Gupta and Jha (2015) argue that even though wireless communications eliminate the requirement for wires to operate the equipment, electricity must still reach the device in some way in order for it to function. Even devices with a relatively high energy consumption can be tested with the help of energy harvesting, which eliminates the need for wires or batteries in the process (Pimenta and Chaves, 2021).

Wireless Sensor Networks (WSNs), which have been an area of active research for several decades, employ sensors which operate without connection to a mains power source. Traditionally this would be with the use of batteries but can also be achieved with a device to harvest energy from the environment around the sensor, which can extend the life of the sensor or eliminate the need for battery changes. This technology has been utilised in commercial and residential buildings for the purposes of energy management, HVAC monitoring and other ‘smart building’ features (Wang et al., 2013; Guan et al., 2017; Musleh et al., 2017). With the advancement in technology allowing ever-smaller devices, self-powered WSNs using TEG energy sources are also being use in aerospace applications (Dilhac et al., 2014).

According to Semenyuk et al. (2018), it is a fundamental requirement in the design of energy-saving smart buildings for both commercial and residential buildings that energy-efficient buildings do not rely heavily on traditional energy sources that make use of fossil fuels. This requirement applies to both commercial and residential buildings. Making commercial buildings intelligent can be critical for the organisations that work there. This is due to the fact that an energy-efficient and modern building can not only save money on energy expenses, but it can also make the working environment more productive for employees. These energy sources are all around us, and with the right tool, they can be converted into electrical energy. For instance, a temperature difference can be converted into electrical energy by a thermoelectric generator (TEG); vibrations can be converted into electrical energy by a piezoelectric element; and sunlight (or indoor lighting) can be converted into electrical energy by a photovoltaic cell (Guo and Lu, 2017). According to Shen et al. (2020), galvanic energy derived from moisture has the potential to be harvested for the purpose of reducing CO2 emissions. These so-called "free" sources of energy are perfectly capable of powering electronic components and systems all by themselves thanks to their suitability. Because they are fully wireless and only use microwatts of electricity, the sensor nodes are already ideally suited for alternative forms of power delivery (Kimionis, 2017). In theory, energy-harvesting devices could be mounted on the facades of buildings; however, this is typically a less cost-effective solution, on the one hand, and it also significantly alters the appearance of the structure and, in the case of widespread application, the cityscape, on the other hand (Kimionis, 2017).

According to Leito, Colombo, and Karnouskos (2016), this is the most complex of all the technologies that people will see, and its implementation enables the generation of energy for homes, factories, and other large applications. Without a doubt, this is the most difficult technology that people will see. Since the cost of solar panels has decreased by 80 percent in the past five years, their installation is now commercially viable and widespread all over the world. Energy harvesting systems take the energy from their surroundings and transform it into electrical energy, which can subsequently be utilised to power a variety of devices, including consumer electronics. On the other hand, Cirimele et al. (2018) claims the development of new concepts that are intended to give the industry an increased production capacity by collecting energy from moving cars as a novel piezoelectricity speed bump.

This section provides an overview on current approaches in local energy harvesting that are being introduced, trialled, or currently implemented within the subject matter of achieving net zero GHG.

2.1.10 Wind, Sound and Vibration Energy Harvesting

Wind, sound, and vibration energy harvesting are pivotal renewable technologies that can substantially contribute to achieving 'Net Zero' in manufacturing. This review synthesises the contributions of key research works in this domain, highlighting the strides made and the gaps my research intends to bridge.

Wind energy is typically harvested with the use of small-scale turbines (Li et al., 2021) that are designed to capture the kinetic energy from ambient airflows. These devices often employ innovative blade designs that are well-suited for the variable wind directions in urban or industrial settings. Work by Kishore et al. (2013) provides some insight into the optimisation of such turbines for low-wind conditions typically found in manufacturing environments, ensuring consistent energy output even from gentle breezes on the other hand, larger wind turbines can produce power in the KW range (Li et al., 2021, Gao et al., 2021).

Sound Energy Harvesting involves the conversion of sound wave energy into electrical energy through piezoelectric or electromagnetic transducers. A comprehensive analysis by Covaci and Gontean (2020) outlines the methodologies for capturing this otherwise lost energy from acoustic sources, showing its potential for powering sensor networks in a manufacturing plant. Vibration energy harvesting captures energy from mechanical vibrations, using piezoelectric materials, electrostatic or electromagnetic mechanisms, these harvesters transform the vibrational energy into electric power. This can be done in areas where sufficient vibration activity is noticed including but not limited to the seismic activity areas, subways, cars, industrial machinery, raindrops etc. Some commonly used transducers in vibration energy harvesting includes the magneto-strictive materials and the piezoelectric (Nabholz et al., 2020, Wang, 2019), work by Anton and Sodano (2007) is seminal in establishing practical applications for piezoelectric energy harvesting from industrial machinery and infrastructure.

Erturk and Inman (2011) provide foundational knowledge in their work, which details how vibrations can be converted into electrical energy. Their investigation into piezoelectric materials and structures offers a bedrock for harnessing ambient mechanical energy, an asset for low-energy-intensive manufacturing settings.

Sirohi and Mahadik (2011) advance this conversation through their study on the efficiency of wind energy harvesters. Their work, elaborating on the methods of integrating piezoelectric devices into wind turbines, enabling energy capture from both wind and structural vibrations, crucial for reducing a facility's carbon footprint.

Moving from the macro to the micro, the paper by Fang et al. (2017), they addressed sound energy's potential. Although it represents a smaller scale of energy, it is a consistent byproduct of manufacturing machinery, and thus offers a continuous source of power.

Lastly, Priya and Inman's (2019) "*Energy Harvesting Technologies*" presents a comprehensive overview of the state-of-the-art energy harvesting technologies. Their insights into the scalability of these technologies are imperative for their implementation in large-scale manufacturing.

These works collectively demonstrate that integrating wind, sound, and vibration energy harvesting into the manufacturing sector offers a realistic pathway towards 'Net Zero'. They highlight achievements in material efficiency, energy capture methods, and novel applications. Building upon these, my research focuses on the integration and optimisation of these technologies within a closed-loop manufacturing system, aiming to minimise external energy inputs and maximising sustainable practices in pursuit of a carbon-neutral footprint.

2.1.11 Solar Energy Harvesting

The source of energy in the solar energy harvesting is the photons generated by the sun during the nuclear reactions inside the sun. these photons travel from the sun to the earth as an electromagnetic wave. These photons/electromagnetic waves are intercepted by the solar panels which converts it into an electrical energy. The frequency bands of harvestable photons by solar panels are shown in

Table 2.2. Besides the visible light spectrum, the photons in the Ultraviolet (UV) and Infrared (IR) are also harvestable by the panels. The energy being carried by the photon can be calculated using equation (2.1). The frequencies of the photons from the sun makes the solar panels to be more effective and preferred choice in some energy harvesting systems. Solar panels are designed using photodiodes with exposed junction for photon to hit. As photons hit the electron of the Si atoms within the photodiode, it moves the valence electron from valence to conduction and gives it sufficient energy to cross the PN junction. This process converts the energy that the photon carries into electrical energy.

Table 2.2 - Operational frequency range of solar panels

Frequency (PHz)	**Band**	**λ (nm)**	**Notes**
0.43	Visible	700	Red
1.6	UV	200	Ultraviolet
-	Visible	-	-
0.27	IR	1100	Infrared
0.79	Visible	380	Violet

2.1.12 Thermoelectric generators (TEGs)

The thermoelectric effect is referring to the generation of electric voltage due to temperature gradient and vice versa. (Farret et al., 2020). A thermoelectric device generates a voltage when the temperature on both sides is different. When a voltage is supplied to it, heat transfers from one plate to the other, resulting in a temperature differential. An applied temperature slope provides an impetus for the charge carriers to move across the plates (Mewada et al., 2018). This effect can be used to generate electricity, measure temperature, or alter the temperature of objects. The applied voltage affects the rate of warming and cooling, hence thermoelectric devices can be used as temperature controls.

TEG is fundamentally a solid-state converter which converts heat to electrical energy directly (Ando Junior et al., 2018). Because TEGs have no moving parts, they are quiet, scalable, and dependable. They are primarily based on thermoelectric materials which are naturally occurring or synthetic materials that produce electric voltage through temperature difference. Generally, such materials possess high electrical conductivity and low thermal conductivity (κ) (Teffah et al., 2018). Low thermal conductivity is crucial for this device because it allows one end of the device to remain cold while the other end experiences an increase in the temperature, thus creating a temperature gradient. The extent of the electrons flow in response to the temperature gradient is provided by the Seebeck coefficient (S) (Teffah et al., 2018). Whereas a given material can be gauged for its efficiency of producing thermoelectric power by its ‘figure of merit’, which is given by:

$$zT = S2\sigma T/\kappa. \tag{2.1}$$

A thermoelectric module is an electronic device that utilises thermoelectric materials to generate electrical energy directly from heat. This technology has gained increasing attention due to its ability to harness otherwise wasted heat and convert it into usable energy. The module's efficiency depends on various factors, such as the choice of thermoelectric materials, the design of the module, and the temperature gradient. Nonetheless, its potential applications in various industries, such as automotive, aerospace, and energy, make it a promising avenue for sustainable energy solutions. A thermoelectric module is made up of two distinct thermoelectric materials: a p-type (with positive charge carriers) and an n-type (with negative charge carriers) and semiconductor, that are linked at their ends (Sun et al., 2019). In response to the temperature gradient, current flows in the circuit. In general, the amount of the current is proportional to the temperature differential. The equation of the phenomenon is given as:

$$J = -\sigma S \nabla T \tag{2.2}$$

The equation under consideration involves several fundamental variables that are integral to understanding the thermoelectric effect. The Seebeck coefficient, also referred to as 'thermopower,' is a measure of a material's ability to generate an electric potential from a temperature difference. The local thermal conductivity, denoted by σ, relates to a material's ability to conduct heat. Finally, the temperature gradient (∇T) represents the spatial variation of temperature across the phenomenon being observed. Together, these variables determine the efficiency of the thermoelectric module and are crucial for the development of high-performance devices. The increased awareness of pollution in the environment has resulted in an increase in technological research to develop environmentally friendly energy resources. TEG uses waste heat to generate electricity, making it an environmentally friendly energy source. In the economic aspect, waste heat is a free source for generating electrical energy (Jaziri et al., 2020). Thermoelectric generators are a combination of a number of smaller innovations being consistently made in the domains of thermal engineering, material sciences, and machine designing. Hence, its development is contingent upon development in these respective fields. Moreover, TEG can operate with varied type of energy being harvested and the technique of harvest is equally as dynamic. These may include light, chemical, thermal, and more recently in the past decade some emphasis has been placed on Radio Frequency, electromagnetic, and piezoelectric. All the different kinds of energy harvesters produce energy from a varying source to convert it into electric power (Liu et al., 2021). Whereas thermal power harvesting comprises the core of the TEG operation in which thermal energy is converted into electric energy through the Seebeck effect (thermoelectric effect).

2.1.13 Materials and designs for Thermoelectric generators

Suski (1995) patented a thermoelectric generator design for use with semiconductor circuits such as those found in conventional PCs. The TEG was placed between the circuit and a heat sink, with a fan cooling the heatsink to increase the temperature differential between the hot and cold sides of the TEG. This design was later improved upon by Solbrekken et al. (2004) and Zhou et al. (2008), who reconfigured the setup to optimise the heat transfer. This increased the power generation of the TEG to a level that it could provide enough power for the cooling fan with surplus available for other purposes.

Since a singular thermoelectric semiconductor layer produces only a small fraction of the usable electric power, thermoelectric generators are composed of several thermopiles, with each thermopile consisting of several thermocouples made from a connected p-type and n-type material (Hu, Edwards and Lee, 2019). The thermocouples are arranged in three classic designs: planar, vertical, and mixed. In a planar design, thermocouples are installed horizontally on substrate starting from the hot plate to the cold plate (Jaziri et al., 2020). A general depiction is shown in the following Figure 2.3.

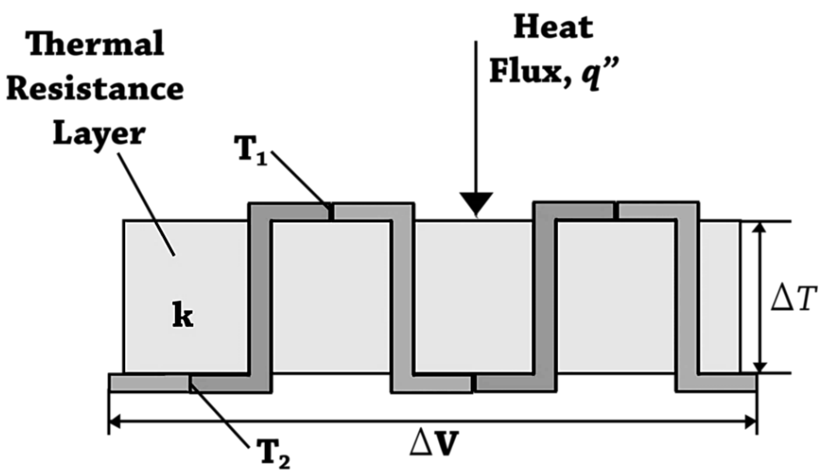

Figure 2.3 - Horizontally arranged thermocouples.

This design enables creation of thin thermocouples and long substrate increases thermal resistance and subsequently the thermal gradient obtained. Vertical design has a vertically installed structure of thermocouples ranging from the hot plate to the cold plate as shown in Figure 2.4.

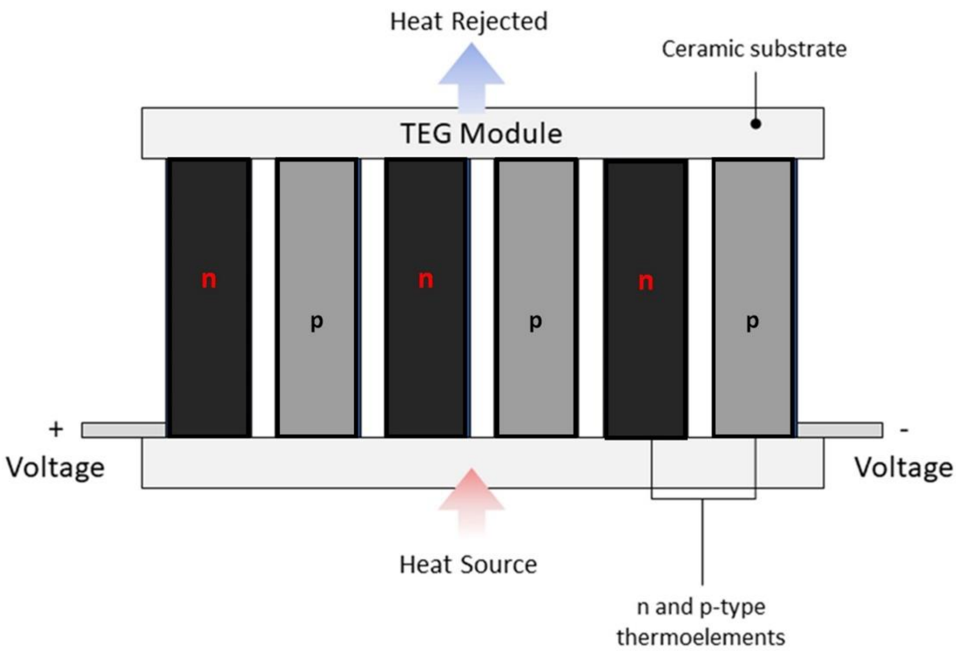

Figure 2.4 - Vertically arranged thermocouples.

This design enables better integration of thermocouples along with high output voltage, making it the most commercially viable design. The power produced 'P_L' on the load R_L connected with a single thermoelement is given by the following equation (Mamur and Ahiska, 2015).

$$P_L = I_L V_L = I_L(\alpha \Delta T - I_L R_{in}) = \alpha^2 \Delta T^2 \frac{R_L}{R_{in}+R_L} \tag{2.3}$$

where, P_L denotes the output power produced on the load run by the TEG, I_L is the electrical current flowing through the load, V_L is the electric voltage generated at the load by operating TEG R_L is the TEG load resistance and R_{in} is the TEG electrical resistance. Here, when R_L becomes equal to R_{in}, the TEG is termed in the matched load condition producing maximum power output, which is provided in equation (2.4).

$$P_{Lmax} = \frac{\alpha^2 \Delta T^2}{4R_{in}} \tag{2.4}$$

Meanwhile, the mixed design is comprised of laterally arranged thermocouples on a substrate thus allowing the heat to flow vertically between the plates. A basic schematic of this type of thermoelement is shown in Figure 2.5.

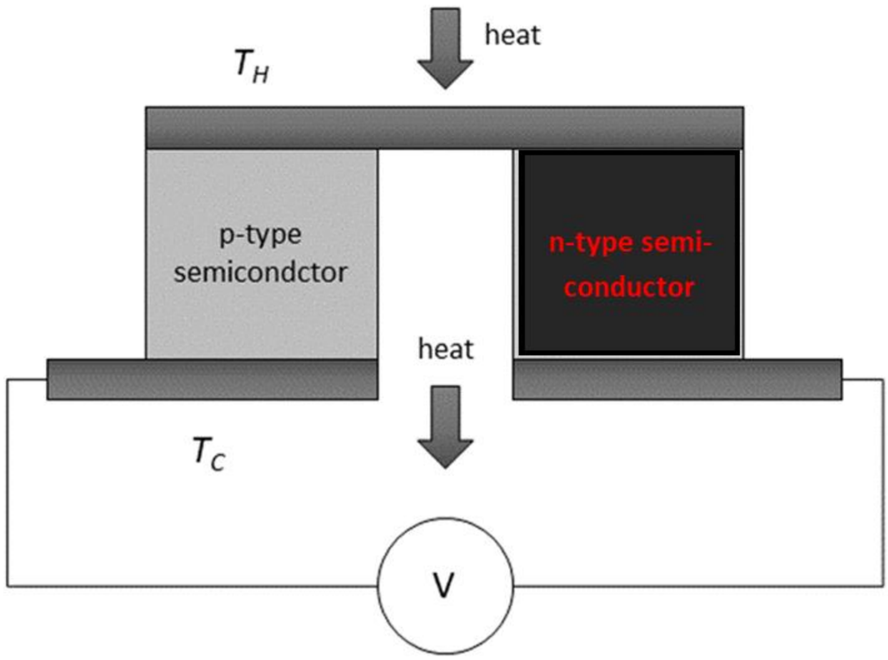

Figure 2.5 - Mixed design of thermocouple

Selection of a thermoelectric material for electric power generation in large quantity requires consideration of a myriad of factors beyond material science. A thermoelectric generator experiences a large thermal gradient between its two plates during operation, which lead to thermal stress. Prolonged exposure to thermal stress causes gradual thermal fracture which mostly occur at the thermoelectric legs, causing the coupling to detach from the legs (Mamur and Ahiska, 2015). Meanwhile, the mechanical properties of the material also influence the overall performance and durability of the thermoelectric generator. These include thermal coefficient of expansion of the p-type and n-type materials so that their thermal coefficients are in compatibility with each other to reduce the possibility of thermal stresses (Jaziri et al., 2020). Material compatibility to avoid incompatibility of relative current is also important and is represented as the ratio of electrical current to diffusion heat current as given by the equation below:

$$S = \frac{\sqrt{1+zT}-1}{ST} \qquad (2.5)$$

Most of the materials demonstrating Seebeck effect are semiconductors. Some of the leading semiconductors that naturally exhibited high power factor and low thermal conductivity are lead telluride (Bet), bismuth telluride (Bi2Te3), and silicon germanium

(SiGe) (Siyafiq et al., 2022). However, because these are also rare elements, with substantial costs, they may not be financially viable for bulk processing in energy harvesting purposes. Most thermoelectric materials known to carry a figure of merit of approximately 1. A typical thermoelectric material will not exhibit this zT value at the same temperatures. For example, bismuth telluride (Bi2Te3) exhibits the zT value of 1 at room temperature, whereas lead telluride value at same temperature is around 500K to 700K (Li et al., 2022). Meanwhile, TEG materials need to have a consistent zT value in the range of 2 to 3 to make them energetically and economically competitive when compared to other power generation systems. With respect to the figure-of-merit (zT), current research suggests that scientists are currently aspiring to create new thermoelectric materials for the power age, with the compound ß-Zn4Sb3, which has a particularly less thermal conductivity and an extreme zT of 1.3 at a temperature of 670K, is an example of these materials (Zhao et al., 2014). This material is inexpensive and also quite stable in a vacuum at this temperature, making it a viable alternative in the temperature range between Bi2Te3 and PbTe. Skutterudites, Tetrahedrites, and precious stone shaking particles are among the novel materials of interest.

Wang et al. (2013) demonstrated a potential application for TEG-powered WSNs in building energy management. The researchers used Bismuth Telluride (Bi_2Te_3), TEG modules, and tested three different configurations of thermocouples. With the aim being to harvest some usable energy that could potentially use within the building or be sold back to the grid.

2.1.14 Novel materials for Radio Frequency TEG designs

Renewable energy source TEGs are those thermoelectric generators which are designed to operate on renewable energy. A basic schematic is shown in Figure 2.6 (labels from Kumar et al., 2019).

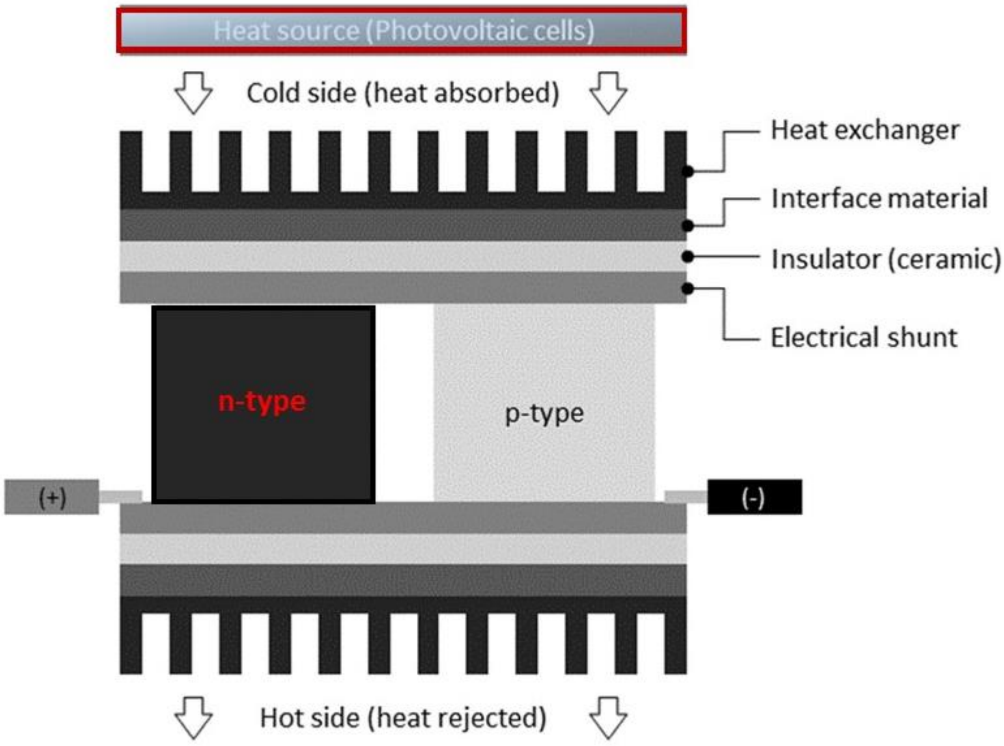

Figure 2.6 - TEG backed solar power generation.

For example, a solar thermoelectric generator (photovoltaic) is constructed to recover heat from solar radiation and convert it into electrical energy. Due to its multifunctionality and facilitation by thin film thermoelements, it is increasingly becoming competitive for conventional photovoltaic cells used in solar power production (Zoui et al., 2020). However, it continues to face relatively low energy conversion efficiency compared to new models of photovoltaic cells. Solar TEGs (STEGs) are characterised by the optical sensor being used like presence of optical concentration system. These are generally cylindrical lenses, parabolic mirrors, Fresnel lenses, flat mirrors, and parabolic concentrators. Whereas non-concentrated solutions are usually used in flat plate collectors and vacuum tubes. In this regard, utilisation of optical concentrators along with heat pipe tubes has been shown to improve the efficiency of STEG. Mizoshiri et al. (2012) constructed a crossover module using a PV module and a thin film thermoelectric. This half-breed module divided light using an infrared channel (hot mirror), allowing only the light that contributed to photovoltaic conversion to pass. The reflected light was centred on the heated side of the thermoelectric module using a focal point at the same time. When compared to the photovoltaic module alone, the half breed thermo-photovoltaic generator's all-out no-heap voltage increased by 1.3 percent. An intensity source, a producer, a channel, and photovoltaic (PV) cells make up the system (Huen and Daoud., 2017).

TEGs are also being studied for their usage in waste heat recovery. Waste heat is the low-grade heat that is regularly emitted into the environment specially from industrial complexes. TEG technology could be efficaciously adopted to the process parameters, thus facilitating in utilising low grade waste heat energy to produce additional electricity. Zou et al. (2018), showed that municipal wastewater could be utilised to generate electricity from thermoelectric generators. The mathematical modelling-based research indicated that approximately 1094 to 70,986 kWh per year electivity could be generated along with saving $163 - $6076. The temperature of the environment plays a big role in important intensity recovery. In hot districts, studies mostly focused on the recovery of intensity lost through cooling frameworks. In colder areas, however, heat recovery tests were more distinct. Killander and Bass (2002) developed and tested a model of a thermoelectric generator that used heat from existing wood stoves in dwellings in exposed and secluded locations of northern Sweden to provide modest amounts of power. In this location, the cost of affiliation with the matrix ranged from $5000 to $120,000 per residence.

2.1.15 Radio Frequency Thermoelectric generator

The concept of energy scavenging is one that has been around for over a century. One of the limitations has however been the ability to capture reasonably large voltages or currents from them, this has limited their ability to be used in multiple arrays of everyday applications – regardless of the fact that the concept has been proven workable, usable and scalable by various research and field testing alike. Figure 2.7 shows the conceptual RF energy harvesting architecture.

"*A unit that emits electrical power from one place and captures it at another place in the Earth's atmosphere without the use of wires or any other supporting medium*" (Brown, 1996)

The description above is the definition proposed by Brown in 1996, however, a microwave-powered helicopter had already been trialled decades earlier in the 1950's (Brown,1969). A more recent source provides the following definition:

"*The concept of power harvesting or energy scavenging was explained as a technique for reaping energy from the external environment using different methods including thermoelectric conversion, vibrational excitation, solar energy conversion, and pressure gradients*." (Tran et al,.2017).

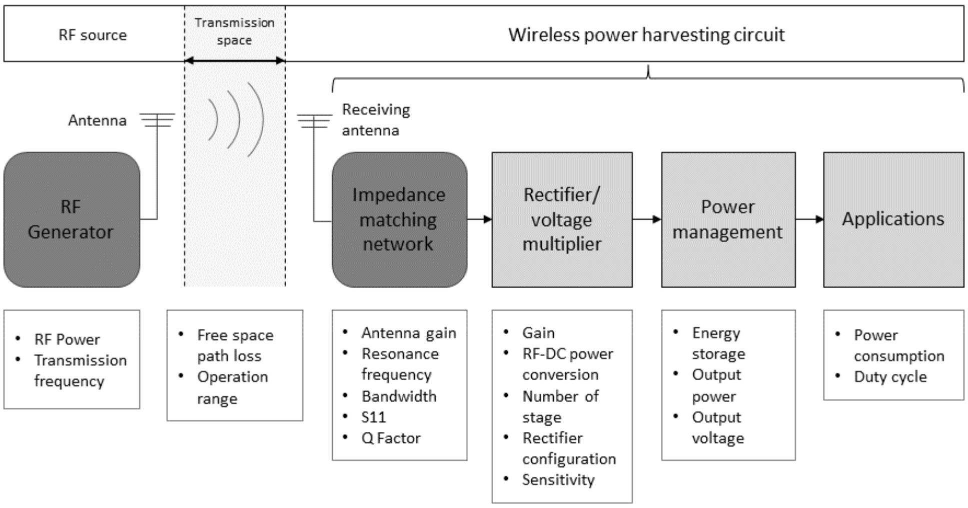

Figure 2.7 - Conceptual architecture of an RF power harvesting system

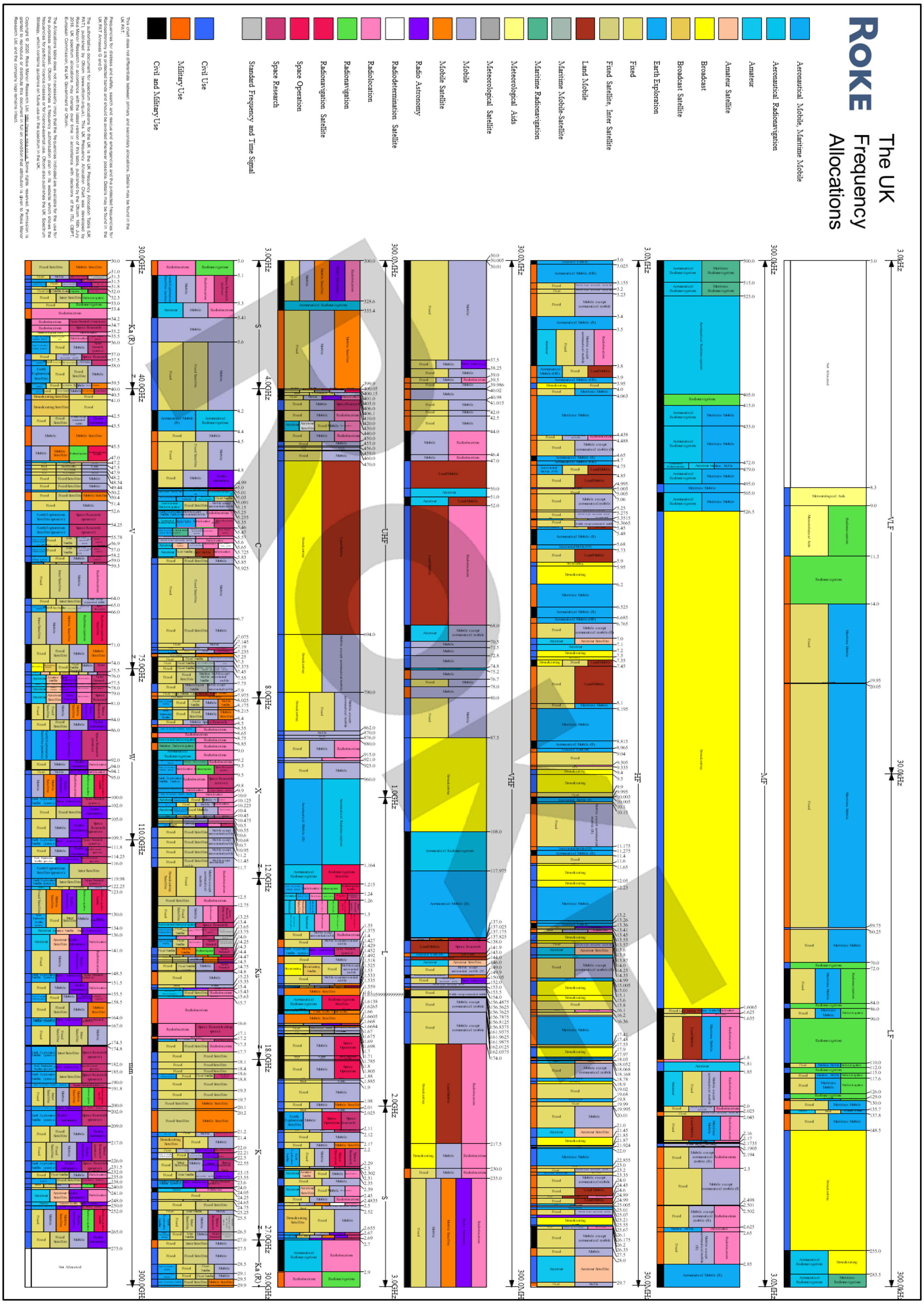

Figure 2.8 - UK radio frequency allocation chart. Source: Roke Manor Research (2020)

The use of thermoelectric generator power capture is an evolving field and confluence of both material sciences and energy engineering. A resulting advantage to this being that development in the material sciences is also being applied in the TEG synthesis aimed at carbon emission reduction to achieve the net zero carbon targets. The TEG machinery is manufactured basically from three distinct class of materials. Low temperature (up to 450 K), high temperature, and middle temperature (up to 850 K), materials for TEG applications can be divided into three classes based on their ideal working temperature ranges (Fan et al., 2015). A variety of materials, including semiconductors, strands, and guiding polymers, have been studied for use in these devices. Current research has shifted towards Chalcogenide semiconductors such as bismuth telluride (Bi_2Te_3) and lead telluride (PbTe), which are being tested for radiofrequency-based synthesis and usage have recently been investigated for TE applications. Due to their Power Factors (PFs), which are advantageous in reducing warm conductivity due to the more vulnerable covalent bonds due to low electronegativity, and the heavy nuclear loads (Syafiq et al., 2009). Because they produce dangerous and scarce components, attention has shifted to more reasonable and abundant chalcogenides, such as tin selenide (SnSe), copper zinc tin sulphide (Cu_2ZnSnS_4, CZTS), and copper tin sulphide (Cu_2SnS_3, CTS) (Lohani et al., 2020). In order to examine the feasibility for low powered electronics, Takayam and Takashiri et al. (2017) synthesised a multi-layered-stack thermoelectric generators utilising radiofrequency (RF) magnetron sputtering. At an annealing temperature of 300 °C, both films showed the greatest power factor values reported at room temperature, namely 12.7 W/(cmK2) for Sb_2Te_3 and 10.2 W/(cmK2) for Bi_2Te_3. As a result, films annealed at 300°C can be used to make multi-layered stack thermoelectric generators. A schematic of a thin-film chalcogenide/AZO thin-film TEG is depicted in Figure 2.9.

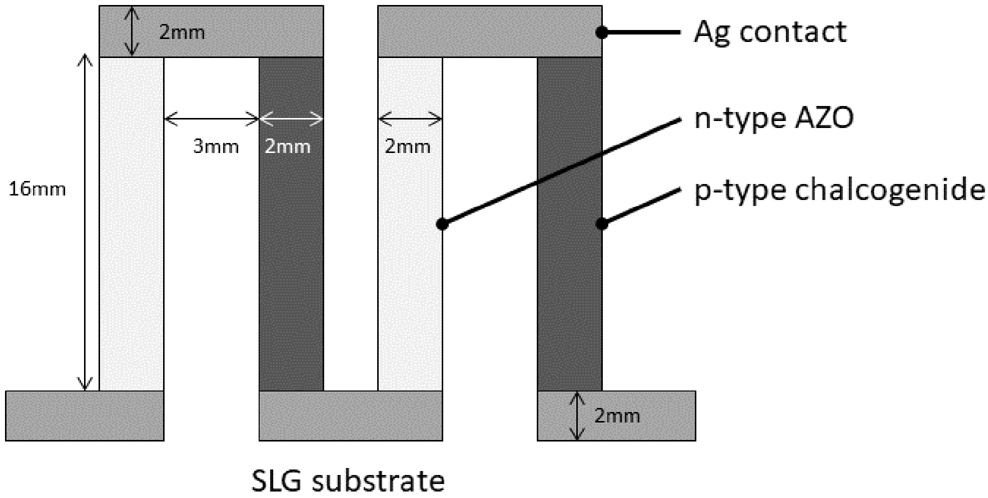

Figure 2.9 - Design of a chalcogenide/AZO thin-film TEG

Among the chalcogenides previously mentioned, bulk Cu2ZnSnS4 (CZTS) is regarded as a reasonable candidate for a supportable and "green" mechanism of high-temperature TE material, as evidenced by its overflow and nontoxicity of constituent components as well as excellent physical, warm, and synthetic properties (Syafiq et al., 2020). Quaternary chalcogenides, such as CZTS, have synthetic and primary levels of opportunity, which allow for adaptability in their actual properties. Additionally, partially or completely replacing sulphur with Selenium can lead to the synthesis of CZTSSe or CZTSe. Compared to the Sulphur, the present Selenium enables the more flexible tuning of the band gap (Jo et al., 2019). In turn, this allows for a more flexible application of the TEG. However, despite concerted efforts for CZTs fabrication in the last two decades, the characteristics of thermoelectricity in CZTs thin film is rarely explored in the literature. A number of studies have emerged aimed at improving the thermoelectric properties of CZTs. For example, cation doping which comprises of copper (Cu) doping has been shown as an effective technique to reduce the thermal conductivity and increase electrical conductivity. Copper tin sulphide (Cu2SnS3, CTS) is among the most extensively researched p-type semiconductor, being investigated due to its non-toxic ubiquitous usage, which makes it an attractive candidate for eco-friendly energy harvesting applications (Syafiq et al., 2022). In recent years, attempts at thin-film TEGs have primarily used standard thermoelectric materials such as PbTe and Bi2Te3. In addition, various attempts employing more sustainable materials, such as SnSe and aluminium oxide, have been reported for oxides and binary chalcogenides (Al2O3). The class for ternary and quaternary Cu chalcogenides, on the other hand, has yet to be discovered. To the best of our knowledge, this is the first-time p-type Cu/Zn/Sn-based chalcogenides have been used to fabricate thin-film TEGs (Syafiq et al., 2022).

Cu/Cu-Ni thin-film thermoelectric generators for energy harvesting were demonstrated by Shimizu et al (2018). 50 pairs of Cu/Cu-Ni thermocouples made up the thin-film generator. Cu and Cu-Ni thermoelectric elements had diameters of 75 m and 225 m, respectively. Both pieces measured 5 mm in length. Cu and Cu-Ni thin films were deposited on low-thermal-conductivity polyimide substrates using radio-frequency magnetron sputtering and shaped using lift-off methods. The temperature differential between the hot and cold sides was roughly 70°C when the hot side of the device was heated to 203°C utilising a hot plate as a thermal source. 2.18 V and 21 W, respectively, were the open-circuit voltage and maximum power. By connecting the device to a capacitor for energy storage, a commercially available light emission diode was successfully operated.

2.2 Energy scavenging integration

Humans have for centuries explored the idea of harvesting energy in order to generate power from varied natural resources. These have historically included but are not limited to tidal waves, solar radiation, oceans, water flow, pressure variations, fossil and nuclear fuels, wind and air flow and temperature gradients (Sorensen, 2004. Dell et all, 2004., Shepherd and Shepherd, 2003). Harvesting Energy from the ambient has garnered more attention and focus until recently. This has historically been due to the fact that traditionally only small levels of energy can be harvested from individual sources (Shearwood et al.,1997., Glynne-Jones et al., 2001). In most cases, ‘energy scavenging’ devices are used as the sole source of energy, where the output is stored within an energy storage device to be used later – typical examples include mechanical wristwatches that stores kinetic energy from the wearer’s arm into a mainspring and subsequently powering the mechanism to keep time.

2.3 Cause effect approach

The fundamentals of any working framework or best practice guidelines stem from the cause and effect of actions and inactions. As a result, literature reviewed looked at the most relevant papers in the last 8 years and collated the findings to provide the foundation towards the direction of a workable and relevant best guidance practice.

For the current study, secondary qualitative design is used as a research design to identify the effective, comprehensive metrics to eliminate the emission of greenhouse gases. Secondary qualitative analysis is selected for this study because it will help in identifying the approaches for the evidence-based primary studies that are prior conducted (Bryman, 2017). The data collected with secondary qualitative design is easy and quick as it does not require any additional tools for data collection. The data collected with secondary qualitative research is fast compared to primary qualitative research (Bryman, 2017).

The collection of data for the study utilised a variety of online databases to identify relevant primary studies. The following online database resources were accessed to find and select relevant publications: Google Scholar, PubMed, Scopus, Web of Science, ScienceDirect, IEEE Xplore and Engineering Village. To ensure the comprehensiveness and relevance of the search, a range of keywords is employed. With literature material selected if they contained the keywords include: "greenhouse gas emissions," "carbon footprint," "batch manufacturing," "sustainable manufacturing," "carbon neutral," "net-zero emissions," "elimination," "emission reduction strategies," "reduction," "KPIs for sustainability," "environmental impact," and "manufacturing emissions." Leveraging multiple databases and a diverse set of keywords ensures a comprehensive and rigorous investigation of the existing literature, paving the way for a solid foundation upon which to build this thesis. The Boolean operators used while searching for the appropriate articles are "AND" and “OR”. A PRISMA flowchart is shown in Figure 2.10.

For the purpose of systematic review or meta-analysis, various frameworks and guidelines exist, each with its own strengths and areas of focus. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) is often preferred over other methodologies due to several key attributes.

Comprehensive and Specific Guidance: PRISMA provides a detailed checklist and flow diagram that ensure comprehensive reporting of reviews and meta-analyses. This level of specificity helps authors to adhere to rigorous standards (Liberati et al., 2009).

Emphasis on Transparency: The framework of PRISMA encourages transparency, allowing readers to fully grasp the research methodology and evaluate the evidence presented. This transparency is critical for replicability and trust in the findings (Moher et al., 2009).

Regular Updates Reflecting Current Best Practices: PRISMA guidelines are updated to incorporate the latest in systematic review methodologies, making them current and relevant. The updates are made by a broad consensus of experts, ensuring they reflect best practices (Page et al., 2021).

By integrating the PRISMA flowchart, this thesis adheres to an established standard in research reporting, thereby reinforcing the methodological rigour of the systematic review

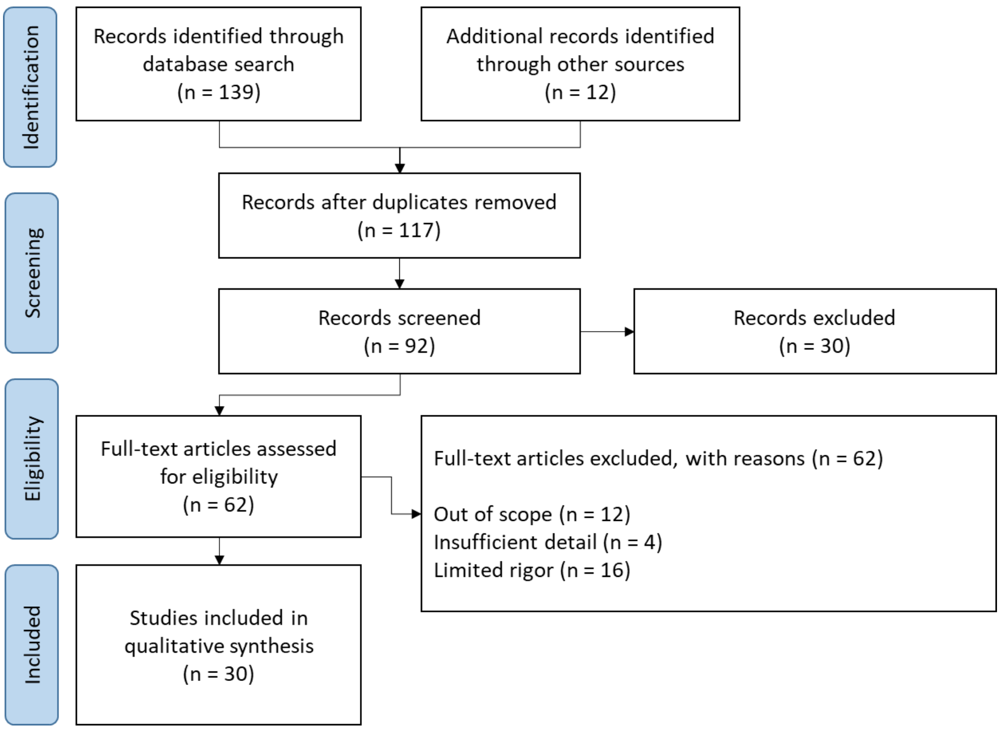

Figure 2.10 - PRISMA flowchart

To identify the appropriate studies for the current research, PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) guidelines are used. According to PRISMA, a total of one hundred and thirty-nine articles were identified; one hundred and eight were from online databases and thirty-one from other resources. After the screening of articles, twenty-two articles were removed because they were duplicates. After further screening of the articles, twenty-five more were excluded because they did not meet the inclusion criteria and were not full-text articles. After assessing the ninety-two full-text articles, thirty were removed because they did not appropriately identify the metric in a concise enough manner.

2.3.1 Inclusion criteria

For the selection of the studies, appropriate inclusion criteria were applied. Studies that were conducted in the recent five years were included to identify the latest emerging strategies. Only primary studies were selected so that effective evidence-based, comprehensive metrics would be identified. Studies that were presented in the English language were included in this research. Studies that were available with full text were incorporated into the study. Only the studies that were relevant to the themes of the current research were included in the study.

2.3.2 Exclusion criteria

Studies conducted more than eight years ago were excluded because they may not capture the latest emerging trends in comprehensive metrics and advances in sustainable manufacturing practices. The following additional exclusion criteria were applied to ensure the relevance and quality of the selected literature.

1. Non-primary research: The study focused on primary research articles to gather first-hand evidence and original findings on the topic.

2. Irrelevance to the topic and themes: Studies that did not directly address greenhouse gas emissions, sustainable manufacturing, or net-zero emissions were

excluded.

3. Abstract-only articles: Studies that provided only an abstract without full-text access were excluded, as they might not offer sufficient information for a thorough evaluation.

4. Non-English articles: Studies published in languages other than English were excluded to maintain consistency and avoid potential misinterpretations during the analysis.

5. Incomplete or preliminary data: Studies with incomplete, inconclusive, or preliminary results were excluded to ensure the rigor and reliability of the findings.

6. Duplicate publications: Articles that presented duplicate or overlapping data from the same research project were excluded to prevent overrepresentation of specific findings.

7. Non-peer-reviewed sources: To ensure the quality and credibility of the research, articles that were not published in peer-reviewed journals or conference proceedings were excluded.

8. Studies with inadequate methodology: Articles that displayed significant methodological flaws or lacked a transparent research design were excluded to maintain the validity and reliability of the findings in the review.

Applying these exclusion criteria ensures a comprehensive, relevant, and high-quality selection of literature sources for the systematic review, which contributes to a robust understanding of the topic and informs the development of recommendations for achieving net-zero emissions in manufacturing. All the studies that do not comprise of the primary research are excluded from this study. The studies that are not relevant to the topic and themes of the current study are also excluded. Studies that are relevant but appeared with only abstract and no full text are excluded. The articles with no English text are also excluded.

2.3.3 Data analysis

For the analysis of the data in this thesis, content analysis is employed which involves establishing themes based on the study's objectives, and interpreting the data collected from previous literature according to those themes (Johnston, 2017). This aids collection of accurate and precise data, allowing for the identification of comprehensive metrics by following the themes for result interpretation. The data analysed through content analysis is also reliable and lends credibility to the research (Johnston, 2017).

In addition to content analysis, descriptive analysis of the data is provided, which serves as a crucial step in understanding the characteristics of the collected data. Descriptive analysis allowed for the summarisation of the data by calculating central tendencies, dispersion measures, and distributions (Trochim, 2006). Descriptive analysis highlights trends, patterns, and relationships within the data, which helps to provide a comprehensive understanding of the research topic and subsequently informed decisions.

The combination of content and descriptive analysis is used to not only identify themes and patterns in the data, but also to quantify the prevalence of these themes, assess the variability within the data, and determine the relationships between different aspects of the data. This approach provided a more robust understanding of the data, thus addressing the descriptive analysis element of this study, and ensuring a comprehensive analysis of the collected information, ultimately contributing to the study's overall validity and reliability. The fully analysed results are thus tabulated in Table 2.3.

Table 2.3 - Summary of papers included in literature review.

S. no.	Title, Author and Date	Objectives	Methodology	Outcomes	Summary
1	Title: Analysis of the Global Warming Potential of Biogenic CO2 Emission in Life Cycle Assessments Author: Weiguo Liu, Zhonghui Zhang, Xinfeng Xie, Zhen Yu, Klaus von Gadow, Junming Xu, Shanshan Zhao & Yuchun Yang Date: 2017	Biomass is widely believed as a carbon neutral. However recent studies have challenged its neutrality by using global warming potential indicator. The objective of the study was to analyse the global warming potential of emissions of biogenic CO2 during the life cycle assessment.	Factors of global warming potential were calculated by using the radiating forcing effects and forest growth model. Time horizon of 100 years was applied. Factors of lifecycle assessment were also applied.	After the analysis of global warming potential, it was identified that biomass plantation showed low global warming potential. The total lifecycle of greenhouse gases emissions were closely related to global warming potential.	Biomass is considered as the carbon neutral material that emits less GHG gas emissions. Different climate metrics have been used to assess the climate change impact on the environment. Many scientists have been using these metrics to assess the rate of emission of greenhouse gases in the environment. These metrics have been used with biomass as well to assess the GHG emission from the biomass. The authors used the forest growth model and radiating forcing affect to calculate the factors of global warming potential metrics. The results highlighted that biomass is contributing to the increase of GHG emissions. Nevertheless, it is considered as a mitigating strategy to reduce the emission of GHG in the environment.
2	Title: Beyond global warming potential: A comparative application of climate impact metrics for the life cycle assessment of coal and natural gas-based electricity Author: DeVynne Farquharson, Paulina Jaramillo, Greg Schivleyγ, Kelly Klima, Derrick Carlson, and Constantine Samaras Date: 2016	The objective of the study is to evaluate the lifecycle greenhouse gas emissions of natural gas and coal used in electricity production plant using climate metrics to test for robustness.	Climate change metrics i.e. global warming potential, technology warming potential, global temperature change potential and cumulative radiative forcing were used for evaluation of GHG emissions. Climate change model i.e. Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) was also used to validate the results.	After analysing the results it was concluded that measurements of all the climate metrics pointed out that natural gas cycle plant have benefits over coal plant and the GHG emissions were less emitted by natural gas plant.	Climate impact metrics have been widely used in many industries to assess the impact of the products used on the climate change. Electricity production sector of turkey also used natural gas and coal based plants for the production of electricity. The authors in this study used three different metrics to assess the emission of GHG in coal and natural gas plants of turkey by using the climate change model. It was concluded that natural gas plants are more beneficial in electricity production sector because it does not emit excessive greenhouse gases emissions.

S. no.	Title, Author and Date	Objectives	Methodology	Outcomes	Summary
3	Title: Electricity production based forecasting of greenhouse gas emissions in Turkey with deep learning, support vector machine and artificial neural network algorithms Author: Bakay, M. S., and Ağbulut, Ü Date: 2021	The objective of the study was to estimate the GHG emissions in the electricity production sector in Turkey.	The study used three algorithms to evaluate the GHG emissions i.e. support vector machine, deep learning, and artificial neural network. For the evaluation of performance of algorithms, five metrics i.e. RMSE, MBE, rRMSE, R2, and MAPE, were also discussed.	According to the results of algorithms, GHG emissions have increased in electricity production sector in Turkey, which is based on fossils-based fuels. Study also concluded that energy production in Turkey is not as high as the emissions from the energy production.	Turkey has large electricity production plants. These plants are often associated with the extensive emission of greenhouse gases in the environment. The author conducted this study to assess the greenhouse gases emissions in electricity production sector of Turkey. The study was performed using different algorithms i.e. deep learning, support vector machine and artificial neural network. Five of the GHG metrics were also used to evaluate the performance. The results concluded the algorithms identified the increased number of greenhouse gases emissions in electricity production sector of Tukey. The results were also verified by using metrics. Mitigation strategies should be implemented to reduce the GHG emissions in the environment.
4	Title: Effects of energy management practices on environmental performance of Indian small- and medium-sized enterprises Author: Patel, J.D., Shah, R., and Trivedi, R. Date: 2022	The study aimed to develop and test an integrative framework linking manufacturing firms' energy management practices (EMPs) to environmental and financial performance, considering energy efficiency and audits. It also examined the moderating role of top management commitment	The research employed structural equation modelling to test hypotheses, with data from a survey of 637 employees in Small- and Medium-sized Enterprises (SMEs) in Indian manufacturing firms	EMPs led to improved environmental and financial performance of firms. Energy efficiency mediated the relationship between EMPs and environmental performance, enhanced by top management commitment. Energy audits mediated the effect of EMPs on energy efficiency.	This study contributes to the understanding of how energy management practices can enhance both environmental and financial performance in manufacturing firms, emphasizing the critical roles of energy efficiency, audits, and top management commitment

S. no.	Title, Author and Date	Objectives	Methodology	Outcomes	Summary
5	Title: Quantifying climate change impacts on hydropower generation and implications on electric grid greenhouse gas emissions and operation Author: Tarroja, B., AghaKouchak, A. and Samuelsen, S Date: 2016	The impact of climate change on the generation of hydropower is deciphered and implications of GHG emissions in operations in California are also assessed.	Electric grid dispatch model and model of major-surface water reservoirs and agitate it with RCP4.5 and RCP8.5 metrics.	Results of the study concluded that the changes occurring in the future climate will lead to the increase in emissions of grid GHG.	Study identified that climate change have significant impact on the technology and vice versa. The authors conducted the study to interpret the impact of climate change on hydropower and also assessed the implications of GHG operations. The study used, two models for the analysis i.e. model of major surface water reservoirs and electric grid dispatch model and also agitated it with two metrics i.e. RCP4.5 snd RCP8.5. Study observed the changes in the emission of GHG from hydropower and concluded that climate change will impact in the increase of emissions from the hydropower grid.
6	Title: Co-benefits of greenhouse gas mitigation: a review and classification by type, mitigation sector, and geography Authors: Deng, H. M., Liang, Q. M., Liu, L. J. and Anadon, L. D Date: 2018	The aims of the study was to analyse the co-benefits of mitigation of greenhouse gases.	To achieve the desired aim, authors conducted a systematic review by analysing 1554 papers using bibliometric analysis.	The study concluded that there are various benefits of greenhouse gases mitigation i.e. health, economic activity, air pollution, resource efficiency and ecosystems.	Reduced emission of greenhouse gases have numerous benefits and majorly contributes towards the reduced harmful impact on the climate change. Authors conducted an extensive systematic review to assess benefits of greenhouse gas mitigation strategies and discussed different benefits. The review was completed by identifying 1554 research articles that were conducted on the benefits of the mitigation strategies of greenhouse gases. The selected papers were analysed using the bibliometric analysis. After the analysis, the results concluded that mitigation of greenhouse gases are associated with improved economic activity, improved health, less air pollution, resource efficiency and healthy ecosystem.

S. no.	Title, Author and Date	Objectives	Methodology	Outcomes	Summary
7	Title: The Cost of Reducing Greenhouse Gas Emissions Authors: Gillingham, K. and Stock, J. H. Date: 2018	The purpose of the study is to evaluate the costs of various technologies that are used in the reduction of greenhouse gas emissions. The emissions are measured with the help of different metrics.	Mckinsey marginal abatement cost curve was use to assess the cost of technology used in reduction of GHG emissions. The reductions were compared by using the metrics to identify the GHG emissions.	Two case studies were discussed and the results concluded that the solar and electric vehicles technologies have fallen sharply.	Reducing greenhouse gas emissions involved the implementation of mitigation strategies that supports the reduction of greenhouse gas emissions. These costs are associated with the technology used to implement the mitigation of GHG. Implementation of mitigation is ensured by analysing the measures of emissions via metrics. In this study, authors used Mckinsey marginal abatement cost curve to identify the cost of reducing GHG emissions. Study concluded that solar panels and electric vehicles are associated with high cost for mitigation of GHG.
8	Title: Organic farming and greenhouse gas emissions: A longitudinal U.S. state-level study Author: Squalli, J. and Adamkiewicz, G Date: 2018	The aim of the study is to examine the relationship between organic farming and greenhouse gas emissions.	The relationship was assessed by collecting the data of US state for GHG emissions due to organic farming. The GHG emissions were evaluated with the use of comprehensive metrics.	The results concluded that organic farming contributes as a mitigating strategy towards reducing GHG emissions because organic farming shows evident environmental benefits.	Organic farming is recently widely used by the farmers as mitigation strategy to improve the quality of soil as well as crops. The farmers used this strategy to contribute towards sustainable agriculture that have minimised impact on environment. The study identified the relationship of organic farming with the emissions of greenhouse gas emissions. The authors used comprehensive metrics to assess the emission of greenhouse gases while organic farming. The authors contributed that organic farming contributes towards less emission of greenhouse gases along with improving soil quality and have various environmental benefits.

S. no.	Title, Author and Date	Objectives	Methodology	Outcomes	Summary
9	Title: Designing a Carbon Tax to Reduce U.S. Greenhouse Gas Emissions Author: Metcalf, G. E Date: 2020	The purpose of the study is to design and analyse the carbon tax approach to reduce GHG emissions in US.	Formulation of carbon tax approach and distribution analysis is done in the study.	The results concluded that the carbon tax approach works when the carbon is adequately measured with the help of metrics and concluded that the approach is effective in reducing GHG emissions.	Authors conducted the study to design effective strategy to reduce greenhouse gas emissions in US. In this study carbon tax strategy is formulated to assess the emissions of greenhouse gases. The tax was implemented on the emission of greenhouse gases which identified the ratio of greenhouse gases in different sector. Carbon tax was successful in reducing the emissions of greenhouse gases in US.
10	Title: Reducing Urban Greenhouse Gas Footprints Author: Pichler, P. P., Zwickel, T., Chavez, A., Kretschmer, T., Seddon, J. and Weisz, H Date: 2017	The study aimed to reduce the greenhouse gas footprints in urban setting.	Study used greenhouse gases footprints metrics as a relevant metric for the mitigation of urban climate change. The study compared GHG footprints of four cities i.e. Mexico, Berlin, New York and Delhi NCT.	The results concluded that the upstream emissions of four cities are in same order, which can be mitigated with effective policies for climate change.	Urban greenhouse gas footprint is the metric to assess the emission of greenhouse gases in the environment of urban settings. The metric identified the climate change impact in the urban area. The study was conducted in four cities comparing their GHG footprints. The results concluded that all four cities shoed precise results in upstream emissions and concluded that it can be mitigated by using different strategies in all four cities.

S. no.	Title, Author and Date	Objectives	Methodology	Outcomes	Summary
11	Title: Assessing farmers' contribution to greenhouse gas emission and the impact of adopting climate-smart agriculture on mitigation Author: Israel, M. A., Amikuzuno, J., & Danso-Abbeam, G. Date:2020	The study's purpose is to reduce greenhouse gas emissions to farmings between the agriculture and mitigation tool.	To identify generalised poisson and poission both across the uniform estimate for IPWRA as well as the emission were evaluated.	The study concluded that farming protection as a mitigating strategy towards reducing GHG emissions. It shows manifest environmental of several benefits.	To improve the farmers is expected practice (CSA) of climate smart agricultural by the adoption the emission (GHG) gas greenhouse curbing to increase the changing climate to the adoption this study identify the (GHG) emitting activities and participation of small holder farmers to causes.to reducing the (GHG) emission on activities of CSA to impact the estimated by it.
12	Title: Performance evaluation of renewable-based sustainable micro-grid under predictive management control strategy: A case study of Gado refugee camp in Cameroon Author: Same, N., Yakub, A., Nsafon, B., Owolabi, A., Mih, T., Suh, D. and Huh, J-S Date: 2022	The study aims to evaluate the feasibility and performance of a hybrid renewable energy system (HRES) for a refugee camp in Cameroon, emphasizing its economic, technical, and environmental aspects	The study employed a predictive management control strategy to design an optimal solar PV/diesel generator/battery hybrid system. It compared three different control strategies: load following (LF), cycle charging (CC), and predictive strategy (PS).	The predictive strategy (PS) was the most suitable, offering the lowest cost and highest eco-friendliness and energy efficiency. The total net present cost (NPC) for electrification of the camp was estimated at $3,809,822.54, with a cost of $0.2018 per kWh. The hybridisation under the PS strategy could annually avoid 991,240.32 kg of emissions..	This research highlights the effectiveness of HRES in improving energy access and sustainability, particularly in remote areas like refugee camps. The study found that predictive management control strategies offer substantial benefits in terms of cost, environmental impact, and energy efficiency

S. no.	Title, Author and Date	Objectives	Methodology	Outcomes	Summary
13	Title: Building sustainability into operations Author: Choi, S., Eloot, K., Lee, D., Liu, S. and von Laufenberg, K Date: 2022	The article focuses on the increasing importance of sustainability in manufacturing, driven by customer demands for cleaner, lower-carbon products. It emphasises how discrete manufacturing organisations are positioned to manage and mitigate their environmental impact	The methodology involves a comprehensive look at various practices and innovations in the manufacturing industry aimed at reducing carbon emissions. This includes examining the role of digitisation in operations and supply chains and how this contributes to environmental sustainability	Key outcomes include the identification of successful carbon reduction programs in discrete manufacturing, which involve bold actions and quick movements towards securing low-carbon materials and positioning as sustainable product suppliers.	The article outlines several key areas where manufacturing organisations are making strides in sustainability: 1) Dual Mission: Balancing profitability and sustainability, often requiring technical changes in product designs and materials specifications. 2) Mobilizing the Supply Chain: Addressing Scope 3 emissions by securing green sources of raw materials and collaborative approaches across supply chains. 3) Design for Sustainability: Focusing on product design phases to create low- and zero-carbon designs.
14	Title: Relationships between industry 4.0, sustainable manufacturing and circular economy: proposal of a research framework Authors: Bag, S., & Pretorius, J. H. C. Date: 2022	To review the latest articles in the area of Industry 4.0, sustainable manufacturing, and circular economy and develop a research framework showing key paths	Qualitative research in two stages: a literature review to identify barriers, drivers, challenges, and opportunities, and a proposal of a research framework integrating Industry 4.0 technology (big data analytics powered AI), sustainable manufacturing, and circular economy capabilities	The research provides a detailed review and proposes a research framework integrating Industry 4.0, sustainable manufacturing, and circular economy, specifically in the context of supply chain management. The paper also proposes a future research agenda and seven research propositions	This paper addresses the impact of Industry 4.0 technology adoption on sustainable manufacturing and circular economy, which has been under-researched. It explores the interplay between these areas and suggests a need for more attention on sustainable manufacturing to develop circular economic capabilities. The proposed research framework aims to enhance circular economy capabilities

S. no.	Title, Author and Date	Objectives	Methodology	Outcomes	Summary
15	Title: World-class sustainable manufacturing: framework and a performance measurement system Authors: Dubey, R., Gunasekaran, A., and Chakrabarty, A Date: 2015	To develop a world class framework for sustainable manufacturing	Survey of managers in manufacturing industries to identify indicators of sustainability; results evaluated against original hypotheses	Framework based on seven key indicators identified from the results of the survey	Authors conducted a survey of managers working in manufacturing companies as a means of obtaining expert opinions about the impact of various pressures (regulatory, organisational, etc.) on performance. From the answers, a framework was produced consisting of a list of indicators believed to be correlated with environmental performance (although not empirically tested).
16	Title: Transformation of the Economy to the Low-Carbon Path of Development: Criteria and Indicators Authors: Maiorova, T. V., Ponomareva, O. S. and Nazarova, O. L Date: 2018	Improve standards of environmental data reporting in Russia’ s transition to low-carbon manufacturing	Reviewed current indicators in Russia’ s environmental management reporting; identified specific factors contributing to carbon emissions which were not included in existing strategy..	A new set of indicators for greenhouse gas emission proposed for integration into Russia’ s existing low-carbon development strategy	Investigates the existing state of Russia’ s low carbon development (LCD) strategy and identifies that important indicators of carbon impact by manufacturing companies are overlooked. A set of indicators are formulated with the goal of integrating them with the existing environmental management indicators.

S. no.	Title, Author and Date	Objectives	Methodology	Outcomes	Summary
17	Title: A quantitative model for environmentally sustainable supply chain performance measurement Authors: Acquaye et al. Date: 2018	The study aims to develop robust mechanisms for supply chain performance measurement as an essential step for transitioning towards sustainable supply chain systems and a greener global economy. It addresses the challenges in measuring the environmental performance of supply chains, such as the lack of standardised methodologies and the inherent multi-criteria nature of the problem	The research leverages the capability of a Multi-Regional Input–Output framework, underpinned by industrial lifecycle thinking, to handle the complex and global nature of supply chains.	Theoretical insights and empirical application of the model to the Metal Products industry of the BRICS nations, modelling carbon emissions trends over a 20-year period (1992–2011) and providing hypotheses on their future emissions performances. It showed that demand is the main driver for the increasing carbon footprint in these industries, but there was an overall decline in reported carbon footprint due to improvements in emissions intensity and technology-induced efficiency gains.	A comprehensive and robust model for environmentally sustainable supply chain performance measurement. Addresses methodological challenges and applied measurement issues by analysing carbon emission trends and factors affecting them in the Metal Products industry across BRICS nations, contributing to the understanding of sustainability transition processes in these countries.
18	Title: Sustainable production system: literature review and trends Authors: Jasti, N. V. K., Jha, N. K., Chaganti, P. K., & Kota, S. Date: 2022	The paper's objective was to conduct a comprehensive literature review and analysis of sustainable production systems (SPS), with a focus on identifying avenues for future research	The study involved analyzing 903 articles published from 1996 to 2019 across 40 journals. The analysis classified articles based on various criteria including time, focus area, methodology, research stream, authorship, industry sector, critical elements, implementation status, type of support, and performance.	Key findings include an increasing trend in empirical and conceptual research articles, the need for implementing sustainable principles in product development, the importance of intercontinental research collaborations, the necessity of implementing sustainable constructs as a coherent set, the need to integrate sustainable philosophy with other manufacturing philosophies, and the requirement for testing and validation of these approaches by researchers.	Comprehensive review of sustainable production systems (903 articles). Findings highlight growth in empirical and conceptual research, emphasize integration of sustainable principles in product development, stress the importance of global research collaborations, and the need for coherently implementing sustainable constructs. The study also underscores the necessity of blending sustainable philosophy with other manufacturing philosophies and calls for rigorous testing and validation of these approaches by researchers.

S. no.	Title, Author and Date	Objectives	Methodology	Outcomes	Summary
19	Title: Combining the worlds of energy systems and material flow analysis: a review. Energy, Sustainability and Society Kullmann, F., Markewitz, P., Stolten, D., & Robinius, M. Date: 2021	To explore how material flow analysis and energy system models can be integrated to better assess the impact of material recycling on energy consumption and greenhouse gas emissions. It also aims to address the barriers and challenges in this integration.	The paper reviews existing material flow and energy system models, focusing on their incorporation of circular economy principles, especially recycling. It evaluates various models and discusses the challenges in integrating these models.	It was found that there is no systematic evaluation of the effects of recycling on future energy system designs, and existing models do not comprehensively evaluate the impacts of recycling. The paper proposes a need for collaborative models developed jointly by the energy system and material analysis communities for more cohesive assessments.	This review highlights the significant yet underexplored intersection between material flow analysis and energy system modelling in the context of sustainable manufacturing. It emphasizes the necessity of integrating these models to better understand and quantify the effects of recycling on energy systems and greenhouse gas emissions, thereby contributing to more effective climate gas mitigation strategies.
20	Title: A cyber-physical systems architecture for Industry 4.0-based manufacturing systems Authors: Lee, J. W., Bagheri, B., & Kao, H. A Date: 2018	To propose a cyber-physical systems architecture for Industry 4.0-based manufacturing systems, with a focus on technology adoption such as the Internet of Things and artificial intelligence.	Used a systematic review methodology to evaluate manufacturing within cyber-physical systems architecture for Industry 4.0-based	Proposed a cyber-physical systems architecture for Industry 4.0-based manufacturing systems, which can improve sustainability through technology adoption.	Identified several lean practices, including process optimisation, waste reduction, and employee engagement, as effective greenhouse gases elimination actions in manufacturing firms.

S. no.	Title, Author and Date	Objectives	Methodology	Outcomes	Summary
21	Title: Mapping environmentally sustainable practices in textiles, apparel and fashion industries: a systematic literature review Authors: Islam, M. M., Perry, P., & Gill, S. Date: 2021	To review literature on environmentally sustainable practices in textile, apparel, and fashion industries, mapping these practices across various manufacturing processes, and developing a conceptual framework for investigating sustainable practices in these industries from an environmental perspective.	A systematic literature review was conducted; bibliometric and content analysis of 91 articles published in peer-reviewed journals over a 10-year period.	The review illustrates the diversity and complexities of environmental practices in the studied industries, highlighting a lack of research in developing country contexts and in upstream stages of garment washing, dyeing, and the manufacture of trims, accessories, and packaging.	This comprehensive literature review maps out environmentally sustainable practices in the textile, apparel, and fashion industries, focusing particularly on upstream manufacturing operations. It underscores the importance of such practices in these industries and the need for more research, especially in developing countries and in certain stages of the manufacturing process.
22	Title: Circular economy in manufacturing: A systematic literature review. Sustainability Authors: Elnaz, N., Lee, J., & Park, J Date: 2020	Conducted a systematic literature review to explore the concept of circular economy in manufacturing, with a focus on product reuse, repair, and recycling.	Used a systematic literature review methodology to explore the concept of circular economy in manufacturing.	Found that circular economy practices such as product reuse, repair, and recycling have significant potential to reduce waste and emissions in manufacturing.	Identified product reuse, repair, and recycling as effective greenhouse gases elimination actions for reducing waste and emissions in manufacturing, with metrics such as waste reduction and resource efficiency.

S. no.	Title, Author and Date	Objectives	Methodology	Outcomes	Summary
23	Title: Knowledge demands for energy management in manufacturing industry-A systematic literature review Authors: Andrei, M., Thollander, P., & Sannö, A Date: 2022	Understand the model for knowledge that has taken industrial energy efficiency to current levels; analyse in the current context of industry transition. Focus on changing social context in relation to energy policies and advances in energy-efficient technologies, which drive a need for change in the manufacturing sector.	Presents a knowledge-based framework including three broader forms of knowledge and specific knowledge attributes to capture the knowledge employed in industrial energy management. Framework applied in a systematic literature review, which analyses forms of knowledge and main aspects of energy management in manufacturing industries. Analysis based on 157 articles published 2010-2020 in journals.	Study finds that technical knowledge is the primary type employed in energy management, with a paradigm shift towards Industry 4.0. Also identifies process knowledge, concerning prerequisite information for implementing energy management, and leadership knowledge as key components. The study suggests that a blend of these knowledge forms could lead to new forms that maximise potential for energy management in manufacturing. Knowledge demands brought about by Industry 4.0 for all forms of knowledge are identified and discussed.	Systematic literature review provides a comprehensive overview of knowledge demands for energy management in the manufacturing industry, with a focus on the transition towards more energy-efficient practices influenced by Industry 4.0. It highlights the importance of technical, process, and leadership knowledge in achieving improved energy management and efficiency.
24	Title: Drivers, barriers and performance outcomes of sustainable packaging: a systematic literature review Authors: Afif, K., Rebolledo, C., & Roy, J. Date: 2022	Provide a comprehensive overview of the literature on drivers, barriers, and performance outcomes of sustainable packaging, to understand the current research state and identify future research opportunities.	The study used the Methodi Ordinatio methodology for a systematic review, retaining 48 relevant and high-impact articles published across 26 academic journals.	Identifies 7 key drivers and three main barriers in sustainable packaging. It finds that these factors are contingent on firm size and that sustainable packaging positively affects environmental, social, and economic performance. However, operational performance requires a proactive, integrated supply chain. The study underscores the importance of integrated packaging decisions at various levels and provides research propositions for future studies.	This review provides a comprehensive framework for understanding the factors that incentivize or deter firms from pursuing sustainable packaging and its performance outcomes. It highlights the significance of integrated decisions for enhancing packaging sustainability.

S. no.	Title, Author and Date	Objectives	Methodology	Outcomes	Summary
25	Title: Going green: Impact of green supply chain management practices on sustainability performance Authors: Ahmad, A., Ikram, A., Rehan, M. F., & Ahmad, A. Date: 2022	The study aimed to assess the impact of green supply chain management practices on the sustainable performance of the textile, automobile, and tobacco industries.	Used a systematic Data were collected from 384 organizations and analysed using SPSS and AMOS software.	The study found that green manufacturing, green purchases, eco-design, and green information systems significantly and positively impact the sustainable performance of organizations. However, cooperation with customers had an insignificant impact. The study also explored the moderation effect of institutional pressures on these relationships.	Research examines five different factors of green supply chain management. It also introduced institutional pressures as a moderating factor, adding uniqueness to the research. The study's findings highlight the positive effects of certain green supply chain practices on organizational sustainability, providing valuable insights for managerial decision-making.
26	Title: Sustainability Assessment in Manufacturing for Effectiveness: Challenges and Opportunities Authors: Kumar, M., & Mani, M. Date: 2022	Critically review sustainability assessment practices in manufacturing from a methodological efficiency-effectiveness perspective. Focus on the evolving requirements and research challenges for effectiveness in sustainability assessment, both in theory (academia) and practice (industry).	Critical review of various sustainability assessment methodologies used by manufacturing organizations to improve their energy, environmental, and economic performance. It addresses the transition in assessment focus from processes to enterprise-level and from single to multiple parameters.	The study provides a clear distinction between efficiency and effectiveness practices in sustainability assessment and discusses the challenges and requirements for achieving effectiveness in these practices.	This research emphasizes the need for effective sustainability assessment practices in manufacturing, considering the increasing environmental burdens and resource scarcity. It highlights the methodological shift in sustainability assessments and the importance of moving towards more holistic and globally sustainable practices. The paper also sheds light on the ongoing methodological developments and the adoption of these practices in the manufacturing sector.

S. no.	Title, Author and Date	Objectives	Methodology	Outcomes	Summary
27	Title: Smart manufacturing and sustainability: a bibliometric analysis Authors: Tiwari, S., Bahuguna, P. C., & Srivastava, R. Date: 2022	The study aimed to understand the relationship between smart manufacturing and sustainability scholarship, providing an up-to-date account of current industry practices.	Bibliometric analysis of 839 articles from the Scopus database, 1994-2022. The methodology involved data collection, analysis, visualization, and interpretation using bibliometric R-package and VOSviewer software.	The study revealed significant insights for scholars, industry professionals, and top management in conceptualizing smart manufacturing and sustainability. It showed a substantial increase in publications from 2015 onwards, with the most productive countries being the United Kingdom, India, the USA, Italy, France, Brazil, and China.	This research reviews the field of smart manufacturing and sustainability, mapping trends over the last two decades. It provides an overview of prolific authors, influential journals, key themes, and the intellectual and social structure of the field. The study indicates that this area is still in early development stages, suggesting the need for more in-depth analysis..
28	Title: A literature review of energy efficiency and sustainability in manufacturing systems Authors: Renna, P., & Materi, S. Date: 2021	The review aims to summarize the most important papers on energy efficiency and renewable energy sources in manufacturing systems published in the last fifteen years.	The papers are grouped considering the system typology (e.g., single machine, flow shop, job shop) or the assembly line, the developed energy-saving policies, and the implementation of renewable energy sources in the studied contexts.	Real world manufacturing systems frequently require heuristics techniques; hence these (and metaheuristics) are heavily represented in state-of-the-art works (in particular, evolutionary algorithms). Less common approaches use fuzzy theory and 12% focus on use of renewable energy. Authors identify need for further investigation of energy efficient scheduling.	The review discusses the main approaches used in the analyzed papers and suggests future directions for integrating renewable energy in manufacturing systems consumption models

S. no.	Title, Author and Date	Objectives	Methodology	Outcomes	Summary
29	Title: Optimal Onsite Microgrid Design for Net-Zero Energy Operation in Manufacturing Industry Authors: Islam, M. M., Rahman, M., Heidari, F., & Gude, V. Date: 2021	Develop an economically viable net-zero energy infrastructure for the manufacturing industry. The focus is on addressing the challenges of uncertain manufacturing system demands, intermittent electricity generation from renewable sources, time-of-use electricity pricing, and integrated operational planning.	Mixed-integer non-linear programming (MINLP) model to design an onsite microgrid system. The model incorporates critical conditions to achieve net-zero energy operation. A linearization strategy is employed to solve the model optimally, and a numerical case study is conducted to assess the model's effectiveness.	Successfully demonstrates the model's ability to design an onsite microgrid system, with fine-grained variations in energy demand and stochasticity of renewable resources. Achieves a balance between energy inflow and outflow and ensuring the economic feasibility of the microgrid installation.	This work addresses the need for sustainable and clean energy infrastructure in the manufacturing industry. By developing an MINLP model, the paper presents a comprehensive approach to designing an onsite microgrid system that can meet the manufacturing industry's energy requirements while achieving net-zero energy operation. The case study further underlines the practical applicability and economic benefits of the proposed model.
30	Title: Lean manufacturing practices and environmental performance Authors: Genç, R. Date: 2022	Investigate the impact of lean manufacturing practices on environmental performance, focusing on the relationship between lean and ecologically oriented variables such as resource usage, energy consumption, and air pollution	Literature review evaluates research findings in this area, discussing principles, methods, current trends, and challenges of lean production as a business model supporting eco-efficiency.	The study highlights the contribution of lean manufacturing practices to better environmental performance in manufacturing systems, emphasizing the importance of green waste concepts in lean manufacturing and its role in promoting environmental efficiency.	This research provides insights into the relationship between lean manufacturing and environmental performance, underlining the effectiveness of lean practices and tools in supporting greener production. It also discusses the improvements in environmental measures and the reduction in ecological impacts for firms that adopt lean manufacturing principles.

2.4 Summary and Implementation

One approach to reduce GHG emissions in the manufacturing environment is to consider the energy requirements of equipment used in production. This can be achieved through the adoption of energy-efficient equipment and practices. For instance, research by Sundaramoorthy et al. (2023) and Chen et al. (2023) has highlighted the effectiveness of energy-efficient equipment in reducing energy consumption and GHG emissions in the manufacturing process.

Another approach is the use of multi-tasking equipment, which can perform several functions at once, reducing the need for separate equipment and, therefore, reducing energy consumption and GHG emissions. Several studies have highlighted the benefits of multi-tasking equipment, including Ganjehkaviri et al. (2017) and Zhao et al. (2023).

DFX can also be used to embed sustainability in the supply chain. This involves working with suppliers to ensure that they meet sustainability requirements, such as reducing GHG emissions and using sustainable materials. Studies by Brun et al. (2020) and Crown Commercial Service (2023) have examined the role of sustainability in the supply chain and its impact on reducing GHG emissions.

Furthermore, the use of modular component build that allows for the reuse, replacement, and serviceability of parts can reduce the need for new components and, therefore, reduce GHG emissions. Research by Tseng, Chang and Li (2008) and Agrawal and Ülkü (2013) have highlighted the benefits of modular component build in reducing GHG emissions and waste.

DFX can also be used to promote the use of renewable energy sources, such as solar and wind power, in the manufacturing process. Several studies have examined the role of renewable energy sources in reducing GHG emissions, including Zhang et al. (2017) and Sharma et al. (2020).

Moreover, the use of optimisation models and decision-support tools can help to identify opportunities to reduce GHG emissions and save money in the manufacturing process. For example, studies by Zeng et al. (2011) and Zhou et al. (2016) have examined the use of optimisation models to reduce energy consumption and GHG emissions in manufacturing.

In conclusion, DFX can be used to implement various carbon-reduction approaches in the manufacturing environment to reduce GHG emissions and save money in the long run. These include considering equipment energy requirements, using multi-tasking equipment, embedding sustainability in the supply chain, promoting the use of renewable energy sources, adopting modular component build, and using optimisation models and decision-support tools. Elements of the all of the above-mentioned methodologies is what this thesis proposes can be incorporated into a singular/holistic approach towards a net-zero manufacturing process.

3. ENERGY HARVESTING ANTENNA

This chapter discusses the methodology of this thesis. It relies solely on data obtained through the implementation of theoretical foundation as implemented from lumped element to microstrip Duplexing antenna design and implementation to using different antennas to harvest energy in batch manufacturing environment. It went further to compare the effects of using different machines during energy harvesting in batch manufacturing environment.

Radio antennas are an essential component of any radio communication broadcast or wireless system. An antenna is necessary for transmitting and receiving signals, making its performance crucial to the operation of the entire radio system. Poor-performing antennas can significantly hinder the effectiveness of the communication system. Therefore, optimizing antenna performance is critical to ensure the success of radio or wireless communication systems. The performance of an antenna is influenced by various factors, such as its design, location, and orientation. Thus, it is crucial to carefully consider these factors to guarantee optimal performance. Maximizing antenna performance is crucial to ensuring the effective operation of radio communication and wireless systems.

Several studies have explored the importance of antenna performance in radio communication and wireless systems. For instance, He and Wang (2023) investigated the optimisation of an antenna system's performance for satellite communication. Anderson et al. (2011) examined the effect of different antenna types and their placement on the performance of wireless communication systems. Furthermore, Zhumayeva et al. (2023) studied the effects of various antenna parameters on the performance of a wireless power transfer system.

3.1 How an antenna works

The primary purpose of a radio antenna is to convert the power supplied to it (in the form of a radio frequency alternating current signal) into an electromagnetic wave that can travel through space and be received by a second antenna as depicted in Figure 3.1. The received electromagnetic wave is then converted back into a radio frequency signal that can be processed by a radio receiver. Although antenna theory can become quite complex, a simplified theoretical understanding of how radio antennas function can be helpful in optimizing their performance for various applications, including energy harvesting.

Several studies have explored the theoretical and practical aspects of antenna design and optimisation. For example, Kumar and Singh (2022) presented a comprehensive review of various types of antenna designs and their applications. Yadav and Chittora (2022) investigated the design of a circularly polarized antenna for wireless power transmission systems. Furthermore, Khorasani et al. (2021) examined the optimisation of an antenna system's performance for wireless communication applications.

An intricate understanding of the full workings and optimisation can be key when setting up a radio communications system or link including in energy harvesting application.

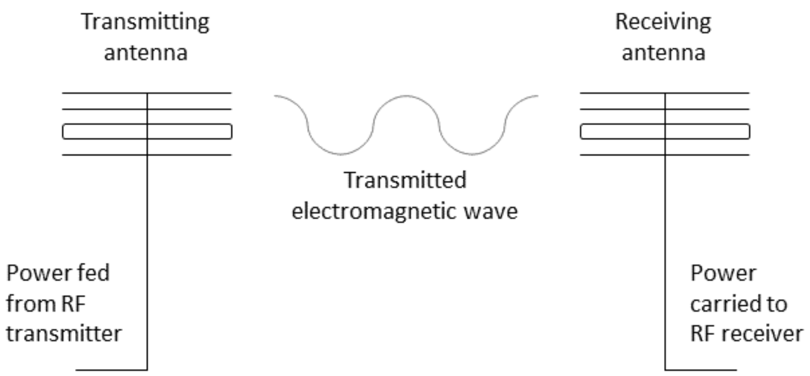

Figure 3.1 - Antenna operation

Antennas work by converting power supplied to them into electromagnetic waves that travel through space and can be received by another (receiving) antenna. The underlying principles behind antenna operation are rooted in the laws of electromagnetism, specifically Maxwell's equations as shown below.

$$\nabla . E = \frac{\rho}{\varepsilon_0} \quad (3.1)$$

$$\nabla . B = 0 \quad (3.2)$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (3.3)$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \quad (3.4)$$

The four Maxwell's equations are fundamental to the understanding of electromagnetism (Jackson, 1998). They are:

Equation 3.1 - Gauss's law for electric fields: The electric flux through any closed surface is proportional to the charge enclosed within the surface.

Equation 3.2 - Gauss's law for magnetic fields: There are no magnetic monopoles; the magnetic flux through any closed surface is always zero.

Equation 3.3 - Faraday's law of electromagnetic induction: A changing magnetic field induces an electric field.

Equation 3.4 - Ampere's law with Maxwell's correction: A changing electric field can induce a magnetic field.

These equations explain how charges move along the antenna to produce electromagnetic waves. As the point charge oscillates in line with the radio frequency signal, the electric field changes, generating a displacement current. This current produces a magnetic field, as per Ampere's Law. The oscillation of the charge, electric field, and magnetic field are all linked, forming electromagnetic waves that propagate outward from the original point charge.

Using Maxwell's equations:

$$J = \gamma E \quad 3.5$$

where J is the current density, E is the electric field strength, and γ is conductivity of the conductor.

$$D = \varepsilon E \qquad 3.6$$

where D is the electric flux, E is the electric field strength, and ε is the dielectric constant.

$$B = \mu H \qquad 3.7$$

where B is the magnetic flux, H is the magnetic field strength, and μ is the permeability of the medium.

Maxwells First law relates the integral of the magnetic field strength around a closed curve is equal to the sum of the conduction and displacement currents enclosed by the curve.

$$Curl\ H = J + \frac{\delta D}{\delta t} \qquad 3.8$$

Maxwells Second law states that the integral of the electric field strength round a closed curve is equal in magnitude but opposite in sign to the rate of change of magnetic flux enclosed by the curve.

$$Curl\ E = -\frac{\delta B}{\delta t} \qquad 3.9$$

Mooijweer (1971, p21) provides an overview of the behaviour of electromagnetic energy. The author explains that whenever there is a disturbance, either of an electric or magnetic nature, at a specific location, it initiates a sequence of interconnected events. This sequence involves the energy involved in the disturbance undergoing a continuous transformation, oscillating back and forth between electric and magnetic forms. This ongoing alternation between electric and magnetic states is not a static process but rather a dynamic one. It is this dynamic change in the form of the energy – from electric to magnetic and then back to electric – that enables the electromagnetic energy to travel or be propagated through the vastness of space. This propagation is a fundamental aspect of how electromagnetic energy behaves and moves in response to initial disturbances, illustrating a key principle in the study of electromagnetic phenomena.

Antenna design and optimisation play a crucial role in their performance. Researchers have investigated various types of antenna designs and their applications, such as graphene-based antenna designs proposed by Zhang et al. (2019) and circularly polarized antenna designs for wireless power transmission systems by Wei et al. (2021). Antenna polarization is another aspect that affects antenna performance. Polarization refers to the direction in which the electric field of the radio wave oscillates. Liu et al. (2013) examined the impact of antenna polarization on wireless communication systems and found that the polarization of the transmitting and receiving antennas must be matched to achieve optimal performance.

Furthermore, the current distribution of the signal on the antenna affects radiation efficiency, as explored by Capek et al. (2015). They found that the radiation efficiency can be improved by adjusting the current distribution. The geometry and shape of the antenna also affect its performance, as studied by Khorasani et al. (2021), who designed a dual-polarized base station antenna system for wireless communication.

In conclusion, antennas are essential components of wireless communication systems, converting power supplied to them into electromagnetic waves. Understanding the principles of electromagnetism, including Maxwell's equations, Ampere's Law, and Faraday's Law, provides the foundation for antenna theory. Research on antenna design and optimisation continues to advance our understanding of antenna performance and its impact on wireless communication systems amongst other applications. With further research, antenna performance can be improved, leading to more efficient and reliable wireless communication systems.

3.2 Further developments – extending the basic principles

Building a radio frequency (RF) antenna for energy harvesting purposes requires an understanding of the basic principles of antenna design. The antenna must be able to efficiently convert the RF signal into electrical energy that can be stored or used to power a device.

One approach to designing an efficient RF energy harvesting antenna is to use a fractal antenna design. Fractal antennas are able to achieve a compact size and wideband frequency response, making them well-suited for RF energy harvesting applications (Nicolaescu et al., 2008). Additionally, fractal antennas can be easily scaled to different sizes while maintaining their performance characteristics.

Another consideration in the design of an RF energy harvesting antenna is the use of metamaterials. Metamaterials are artificial materials with unique electromagnetic properties that can be used to improve the performance of an antenna. For example, metamaterials can be used to enhance the efficiency of energy transfer between the antenna and the harvesting circuit (Zhou et al., 2021).

Finally, it is important to consider the impact of the antenna's environment on its performance. Factors such as nearby objects and interference from other RF sources can affect the antenna's ability to harvest energy. Therefore, careful consideration of the antenna's placement and design is necessary to ensure optimal performance (Wagih et al., 2020).

3.2.1 RF Energy Harvesting

Radio frequency (RF) waves are a type of electromagnetic radiation that arises from the oscillation of photons within pre-defined frequency bands, such as UHF, SHF, or VHF. These waves propagate through space, carrying energy and information between a transmitter and receiver. They are widely used in various applications, including communication systems, radar, and medical devices, owing to their ability to travel long distances and penetrate obstacles. As technology continues to advance, so does the potential for new and innovative uses of RF waves in fields such as wireless power transfer and internet of things (IoT) devices amongst other applications. Here, the source of the photon is an electronic device with a predefined electromagnetic radiation, unlike that from a natural radiation like the sun used by solar panels for energy harvesting. As mentioned earlier, the electromagnetic properties of the RF radiation are determined by the transmitter of the electronic device in the RF range (e.g., UHF from

300MHz to 3GHz). This RF range is substantially lower than that of the frequencies of the photons from sun hitting the solar panels which is between 270 THz to 1600 THz. This is translated to 5-6 orders of magnitude lower energy per photon in the RF energy harvesting when compared to the solar energy harvesting. Equation (3.10) can be used for this comparison which led to the limitation of the RF energy harvesting application to extremely small systems.

$$E = hv = \frac{hc}{\lambda} \tag{3.10}$$

Where v is the oscillating frequency of the photon which corresponds to the wavelength λ. h is the planck constant which represents the energy carried by the photon per cycle of oscillation.

3.3 Microstrip Antenna

A microstrip antenna (also known as a printed antenna) is an antenna fabricated using photolithographic techniques on a Printed Circuit Board (PCB) (Farahani, 2008). It is mainly used in the microwave frequencies. A typical patch antenna comprises a metal foil, typically of different shapes, affixed to the surface of a printed circuit board (PCB). The metal foil serves as the radiating element, while a metal foil ground plane is located on the opposite side of the board. The design of the patch antenna can be tailored to specific frequency ranges, making it a popular choice in various applications, such as wireless communication and satellite systems. Its simple construction, low profile, and ease of integration into electronic devices make it a preferred option for engineers and designers seeking compact and efficient antenna solutions - in some cases, the microstrip antennas consist of multiple patches in a two-dimensional array.

The patch antenna is primarily characterised by two significant dimensions: the active length, denoted as “L”, and the width, represented as “W”. These dimensions play crucial roles in the antenna's functionality (Balanis, 1996, p728). Specifically, the active length "L" is instrumental in determining the primary resonant frequency of the antenna.

This resonant frequency is a key aspect of the antenna's performance as it dictates the specific frequency at which the antenna most efficiently receives or transmits signals. On the other hand, the width "W" of the antenna is a critical factor in controlling its radiation efficiency. Radiation efficiency is a measure of how effectively the antenna can convert the input power into radiated electromagnetic waves.

In the scenario of a dual-band patch antenna, a unique arrangement is often employed where the active length “L” for one frequency band is ingeniously designed to serve as the width “W” for the second frequency band. This design allows the antenna to operate efficiently at two different frequency bands. However, this clever design comes with a notable compromise, particularly in terms of the radiation efficiency for both bands. In this dual-band configuration, the width terms “W”, which are essential for determining radiation efficiency, are inherently constrained by the requirements of frequency tuning. The frequency tuning, which is pivotal for the antenna’s operation at the desired frequencies, thus dictates the dimensions of “W”. As a result, achieving optimal radiation efficiency for both frequency bands becomes a challenging balance, as the width “W” must serve dual purposes in this arrangement, each linked to a different resonant frequency

The microstrip antennas are usually connected to the transmitter or receiver using foil microstrip transmission lines. The patch antenna is the most commonly used microstrip antenna and can be used to design antenna array by using multiple patches as cognitive elements. Patch antennas exhibit unique characteristics, such as a narrowband or wide beam, depending on their design parameters. These antennas are typically created by etching conductive metal sheets into specific patterns and bonding them to an insulating dielectric substrate. A continuous metal layer is then bonded to the opposite side of the substrate, forming a ground plane. This construction method allows for precise control over the antenna's dimensions and enables the patch antenna to operate at specific frequencies. Due to its low profile, ease of integration, and directional radiation patterns, the patch antenna has become a popular choice for various applications, including mobile phones, wireless networks, and satellite communication. The patch antennas are available in several shapes, with square, rectangular, circular, and elliptical being among the most common designs. Some patch antennas are constructed using metal patches and ground planes that are separated by dielectric spacers, allowing for a wider bandwidth and greater flexibility in terms of antenna shape. Despite their low profile and rugged construction, these antennas are capable of conforming to a variety of shapes, such as the curving skin of aircraft or spacecraft. As a result, they are often mounted on the exterior of such vehicles, providing reliable and efficient communication capabilities. It can also be incorporated into different shapes and devices like mobile radio communications devices. Due to its ease of fabrication using printed circuit board, ease of integrating the antenna on the same board with the rest of the circuit, and the possibility of adding active devices to the antenna itself to make active antennas (Prakash et al., 2022), the microstrip patch antenna has become a preferred choice in communication and energy harvesting systems.

3.4 Harvesting Antenna Design Synthesis

This section of this thesis considers the design, test fabrication, validation and verification of antenna design as well as the selection process of choosing the optimal antenna for the purpose of energy harvesting. The test facility and resource/time constrain during the testing phase of this work meant that the use of an anechoic chamber was not possible. The test facility had an RF screened room - this would not have been ideal to use, as the internal metal walls would result in significant reflections that create errors in any attempt to measure the emission or reception characteristics of an antenna.

In order to account for various factors, a direct approach was taken in the experimental setup by measuring the signal levels, which also included the ambient noises present in the environment. This measurement is necessary to establish a baseline for comparison. The baseline was critical as it provided a reference point against which the signals could be evaluated. When the results of these measurements were analysed, it is observed that the signals of interest were distinctly higher than the noise floor detected by the Spectrum analyser. The noise floor, which represents the lowest level of detectable signal in the system, is a crucial benchmark in signal analysis.

Given this observation in validating the performance, it is important to emphasise that the signals that were reported in the study are relative in nature. They are not absolute measurements but are instead relative to the specific combination of the antenna used and the Spectrum analyser. This relative nature of the signal measurement is a key aspect to consider when interpreting the results. It implies that the reported signal strengths are influenced by the characteristics and performance of the antenna and the Spectrum analyser. Therefore, the reported signals should be understood as an indication of the signal levels as perceived through this particular setup of the antenna and the Spectrum analyser, rather than as independent or absolute values. This consideration is crucial for accurately assessing the effectiveness and efficiency of the antenna in its operational environment.

The methodology also considers the impact of equipment, factory layout and the typical setup found within a batch manufacturing environment. Additional consideration is also given for the upper limit of radio frequency exposure as dictated by HSE directive within the laboratories at the University of Hertfordshire.

3.4.1 Quarter wavelength Antenna

The quarter wave antenna is designed using the basic antenna design principles. As the name suggest, quarter wave (λ/4) derives its name as the radiating element is designed to have the length of a quarter wave. A typical design will see the radials around 12% longer. The design utilises 4 radials in a bid to achieve maximum stability when placed unsupported. This design is a true unbalanced antenna, as variations within its structure can alter its feed impedance from around 36Ω up to 50Ω. The former is the optimal theoretical setup and is achieved when the radials are set to 45°and the former is achieved when the radials are set to 42°. The efficacy of these types of antennas have been verified by several authors (Dai et al., 2013, Lin et al., 2006, Wei et al., 2012 and Sun et al., 2009), thus this design is considered to form a concrete test/validation component in the process of testing and benchmarking antenna performance functions. Figure 3.2 shows the final design on the test bench. Due to the inability to fully calibrate the designed quarter wave antenna (owing to limited equipment within the laboratory), an externally OE-manufactured and calibrated dipole was also used to validate the results obtained from the quarter wavelength antenna built. Full details of characteristics and certification of the used dipole are included within the appendix of this thesis.

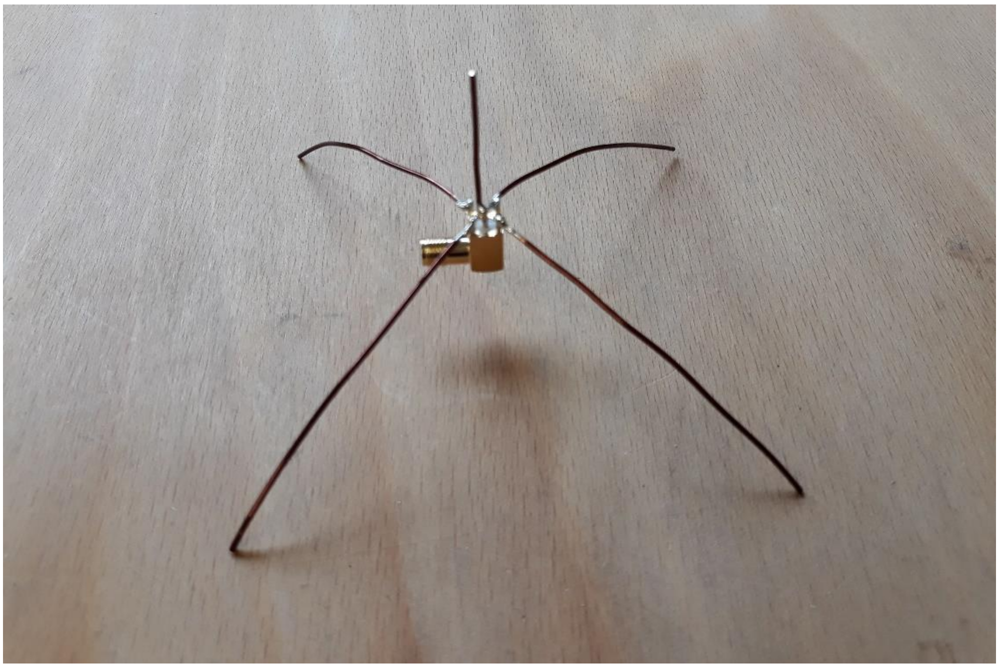

Figure 3.2 - Designed and built quarter wave antenna

The 2.4GHz 1/4 wave antenna has a centre radiator length of 28.6mm and ground wires of 78mm. Actual tuning is near 2.5GHz. The centre radiator length is calculated as per Equation (3.11).

$$L = \frac{c.VF}{4F_O} \tag{3.11}$$

Where: c is the speed of light (3e8 m/sec), VF is velocity factor (approx 0.95 for wire antenna) and Fo is the resonant frequency (Hz)

Ground wires to be > n.λ/4, not near = λ/2.

3.4.2 Lumped Element Duplexing Antenna

The Duplexing antenna is first designed using the lumped element synthesis. The numerical calculations used in the synthesis is geared towards the duplexer specifications (Ogbodo, 2017) which are to have two channels. One channel for the receiving (Rx) and another channel for transmitting (Tx). These are operating at frequencies of 1.8 GHz and 2.4 GHz, respectively. Each channel is designed with a fractional bandwidth of 4%, resulting in the Rx channel spanning from 1.764 GHz to 1.836 GHz, while the Tx channel covers 2.352 GHz to 2.448 GHz. To ensure optimal performance, a return loss (RL) of -20 dB is specified for both channels.

It is important to point out that the measured S11 parameter is specifically related to the output of the filter, that is, Z0 upper and lower as depicted in Figure 3.6 of the study. This parameter is crucial as it indicates the degree of impedance matching at these specific points in the circuit. However, it should be noted that the antenna side, represented by R0, is not directly accessible in the patch antenna configuration. As a result, the precise level of matching between each filter section and the antenna in the constructed version remains unknown.

Ideally, in a perfect system, a signal at 1.8GHz received by the antenna should predominantly be present only in the output of the corresponding 1.8GHz filter, which can be referred to as the upper filter in Figure 3.6. In this scenario, the signal at the 2.4GHz channel, denoted as Z0lower, should be significantly lower, preferably less than -10dB. This concept is crucial in ensuring that each filter effectively isolates its designated frequency.

The degree of "isolation" between the two channels can be theoretically assessed by applying a signal at Z0upper and measuring the output at Z0lower, which corresponds to the S21 parameter from port 1 (Z0upper) to port 2 (Z0lower). However, it is important to note that this particular measurement is not conducted for this study, owing to constrained resources as supported by Cripps (2006) and Bowick (2007) emphasising the real-world challenges encountered in conducting extensive RF measurements, especially in environments where resources are shared or limited.

From a system design perspective, the interaction between stray signals and the transmission (Tx) device at 2.4GHz and the reception (Rx) device at 1.8GHz is critically influenced by the isolation requirements of the antenna. Ideally, sufficient isolation would mean that neither the Tx nor Rx designers need to be overly concerned about the impact of stray signals on their respective devices. Specifically, the Rx path at 1.8GHz would require a higher degree of isolation from the 2.4GHz signal than vice versa. This is because a strong 2.4GHz signal could potentially cause the Rx's automatic gain control to reduce its sensitivity, thereby diminishing its overall effectiveness.

Importantly also, it is crucial to understand that a good impedance match, as indicated by the S11 parameter at the input of the filters, does not necessarily guarantee good isolation. The isolation is more a function of the frequency response of the system.

Figure 3.14 in the study illustrates that both S11 (matching at the 1.8GHz port) and S22 (matching at the 2.4GHz port) demonstrate good performance. This indicates that at each frequency port, the impedance matching is effectively achieved, which is a positive aspect in terms of the overall system design.

Furthermore, each channel is designed with a three-pole configuration and a Chebyshev ripple factor of 0.043 dB as obtained from (Ogbodo et al., 2016; Zobaa and Abdel Aleem, 2021). The low-pass prototype response serves as the foundation for these designs, enabling the channels to effectively filter out unwanted frequencies and maintain the desired signal quality.

The terminal immittances of the low-pass prototype responses were denoted as g-values, where $g_0 = g_4 = 1.0$, $g_1 = g_3 = 0.8516$ and $g_2 = 1.1032$. The g-values were numerically used to obtain the capacitive and inductive values of the lumped element components, as well as the J-inverter values used for frequency transformation.

Equations (3.12) and (3.13) were utilised for obtaining the capacitive and inductive values of the resonant frequency of the lumped element components, respectively. Whereas equations (3.14) to (3.16) are utilised for evaluating the J'-inverter values of J'_{01}, J'_{12}, and J'_{23} of the lumped elements respectively (Ai et al.,2016, Xu et al.,2008). To obtain the capacitive coupling values, the J'-inverter values had to go through a frequency transformation by dividing them with w_0 (Equation 3.12), this frequency transformation yielded the capacitive coupling values as shown in Table 3.1. Table 3.1 shows the obtained values from equations (3.12) to (3.16). These values were used for the lumped element model of the designs shown in Figure 3.3 and Figure 3.6 for the channel filtering antennas and the Duplexer antenna respectively. Figure 3.4 and Figure 3.5 show the simulated responses of Figure 3.3 for the Rx channel and Tx channel filtering antenna respectively. Figure 3.7 shows the simulated response of Figure 3.6.

$$C = \frac{g_1}{w_0 Z_0 FBW} \tag{3.12}$$

where $w_0 = 2\pi f_0$ and f_0 is the fundamental frequency,

$$L_{eff} = \frac{C_0}{2 f_0 \sqrt{\varepsilon_{eff}}} - 2\Delta L \tag{3.13}$$

where C_0 is the speed of light in free space and L_{eff} is the effective length of the resonant element, ε_{eff} is the effective dielectric constant, and ΔL is the line extension as expressed in Equation 3.16.

$$J_{01} = \frac{g_0}{Z_0} \tag{3.14}$$

$$J_{12} = \frac{J_{23}}{\sqrt{2}} \tag{3.15}$$

$$\Delta l = 0.412h \left[\frac{0.262 + \frac{w}{h}}{0.813 + \frac{w}{h}}\right] \left[\frac{\varepsilon_{eff} + 0.3}{\varepsilon_{eff} - 0.258}\right] \tag{3.16}$$

Table 3.1 - Calculated parameters from equations 3.12 to 3.16

	C-pF	L-nH	J'01	J'12	J'23	J01-pF	J12-pF	J23-pF
Rx	37.645	0.2077	0.02	0.012	0.018	1.099	1.768	1.554
Tx	28.233	0.1558	0.02	0.012	0.018	1.326	0.824	1.165

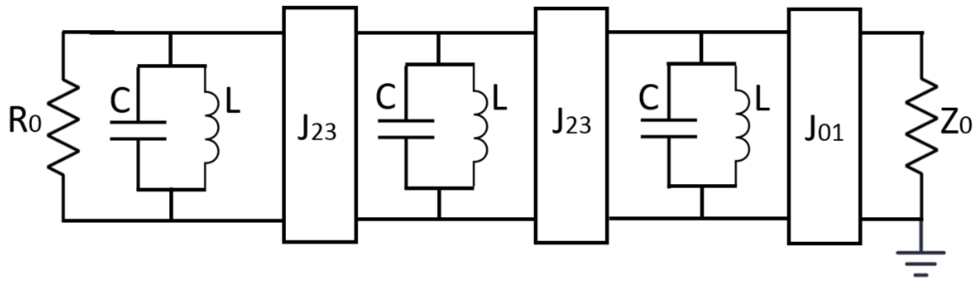

Figure 3.3 - Filtering antenna channels for Rx and Tx channels

It should be noted that in all the antenna response graphs, the Y axis is the S-Parameter given in dB and the X axis is frequency measured in GHz. For simplicity when measuring the harvestable energy, graphs are presented with the Y axis given in mV.

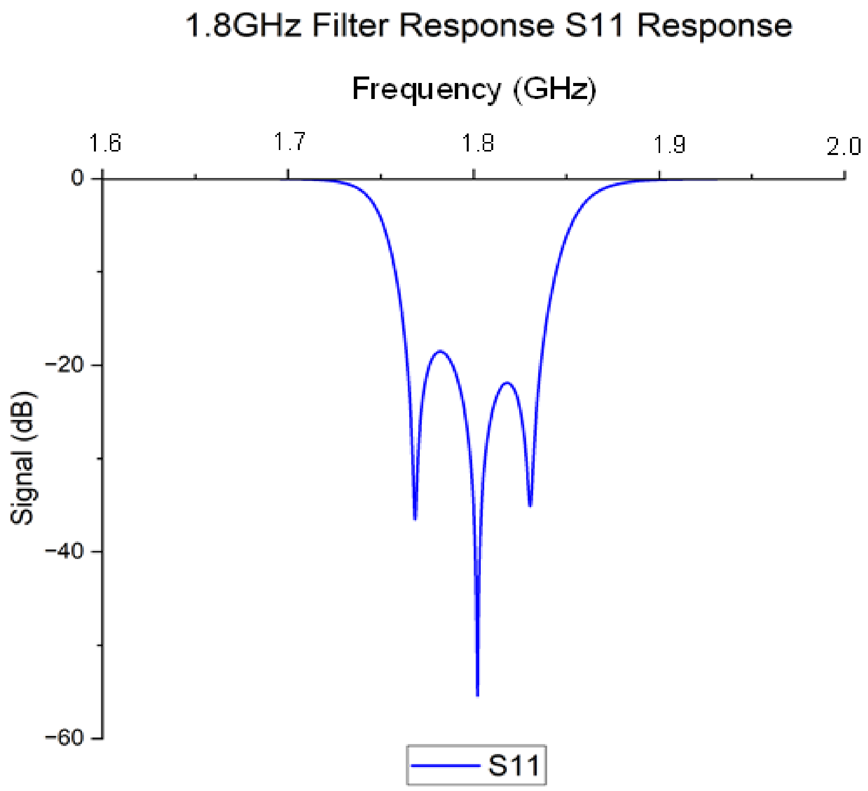

Figure 3.4 - Rx of 1.8 GHz Filtering antenna response

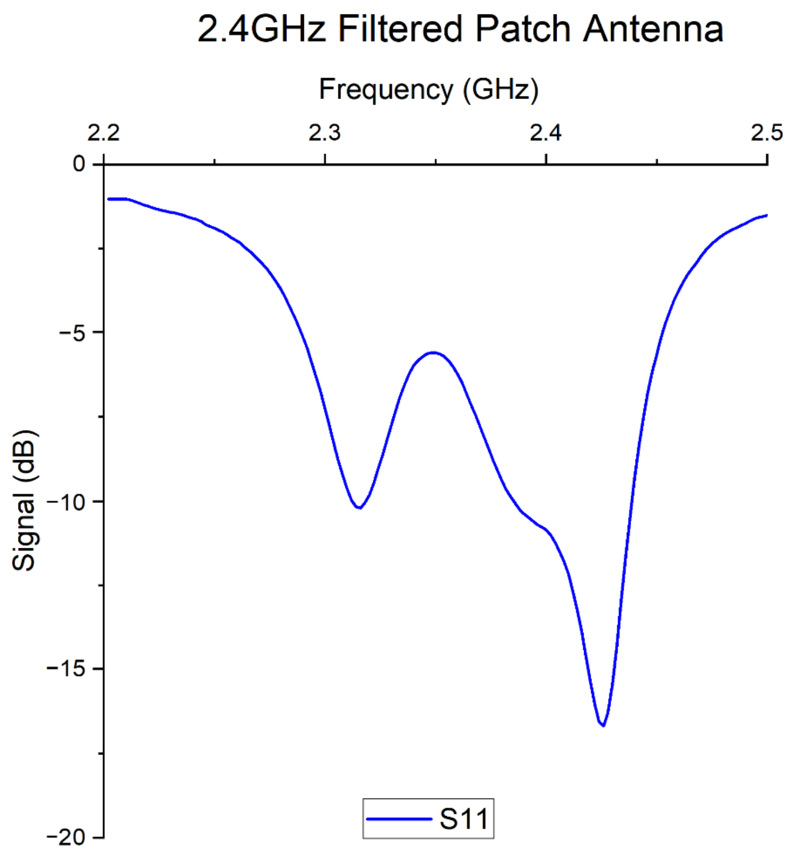

Figure 3.5 - Tx of 2.4 GHz Filtering antenna response

From Figure 3.4 and Figure 3.5, it can be noticed that there are three poles in the return loss. This indicates the contributions of all the resonators in the filtering antenna response which includes the antenna that functions as resonators as well. A sharp roll-off can also be noticed on both responses, this indicates a good separation from adjacent channels which is suitable in a crowded system. It is worth mentioning again, that in the Figure 3.6, the Rx and the Tx channels are joined together using a single resonating antenna which operates on both Rx and Tx channels of 1.8 GHz and 2.4 GHz respectively.

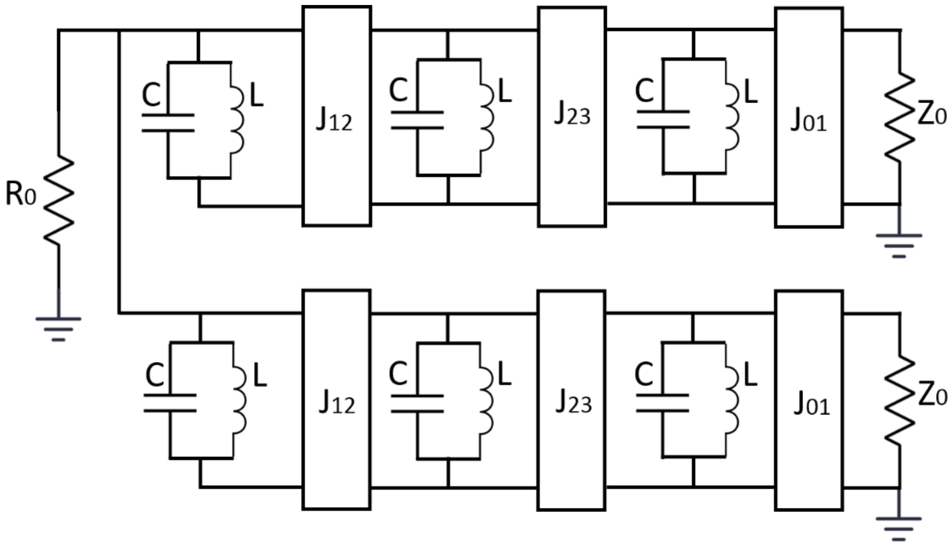

Figure 3.6 - Duplexer antenna

The complex input impedance of the patch antenna is denoted as R0. This particular impedance acts as the foundational source impedance in the process of designing filters for the antenna's receive section. Simultaneously, it serves as the critical load impedance for the section dedicated to transmitting signals. This dual role of R0, as both source and load impedance, is integral to the operational effectiveness of the patch antenna in its respective transmit and receive sections, ensuring optimal signal processing and transmission.

From the response in Figure 3.7, the presence of three poles can be seen in the return loss response of both channels of Rx and Tx. This indicates the contribution of the resonating antenna junction as a resonator in the circuit. The circuit's compactness is achieved through the incorporation of the resonant antenna junction, reducing the total number of resonators from six to five (Pozar, 2011; Balanis, 2016). Moreover, in the context of lumped element antenna design, a commendable isolation between the two channels is observed, registering approximately -57 dB on the Tx (2.4 GHz) channel and -84dB on the Rx (1.8 GHz) channel (Pozar, 2011; Balanis, 2016). These improvements contribute to the overall efficiency and performance of the antenna system.

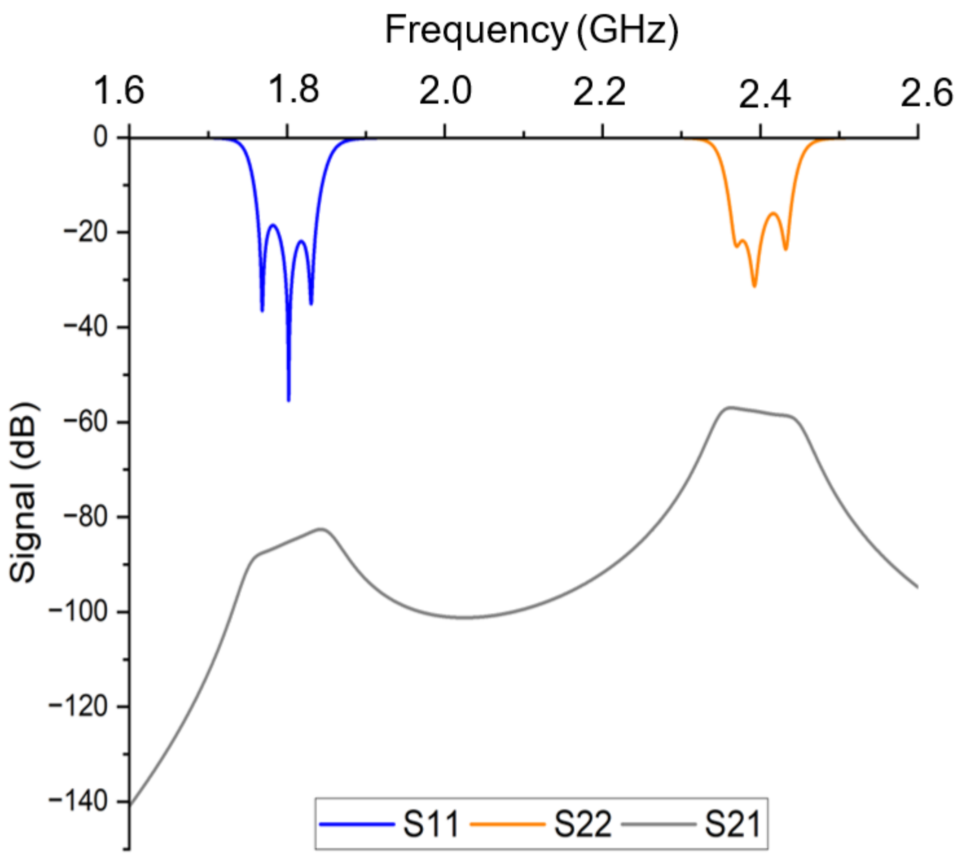

Figure 3.7 - Duplexing antenna response

3.4.3 Microstrip Duplexing Antenna Design

The consideration of Microstrip Duplexing Antennas is pivotal to the underlying aim of exploring energy harvesting strategies and upcycling for achieving net-zero emissions in manufacturing. This antenna design setup forms an integral part to the exploration of innovative energy harvesting techniques, aligning with the strategic utilisation of RF and TEGs in batch manufacturing as outlined in earlier sections particularly, sections 1 and 2 of this thesis.

The Microstrip Duplexing Antenna is particularly significant due to its frequency efficiency and compact, integrated design. As noted by Balanis (2016), duplexing antennas are designed to operate efficiently over multiple frequencies, which is essential in energy harvesting applications where capturing a wider range of frequencies can lead to more efficient energy conversion. This dual-band or multi-band capability enhances the effectiveness of RF energy harvesting, thereby contributing to the overall energy efficiency of the manufacturing process.

Furthermore, the compact and integrated design of duplexing antennas, highlighted by Pozar (2011), aligns with the principles of 'Design for X' (DFX), where X represents environmental sustainability (themed towards net-zero). The integration of advanced antenna design with environmental sustainability goals in manufacturing is a practical application of the theoretical concepts discussed in earlier sections, such as the novel materials for RF TEG designs (section 2.1.14) and the adoption of modular component building in batch production (section 1.2.4).

As previously mentioned, In the proposed design, a resonating antenna is combined with two channel filters to achieve optimal performance. These filters are specifically designed to meet the rigorous standards of a three-pole Chebyshev ripple factor of 0.043dB. The lowpass prototype serves as the foundation for the filters, providing a blueprint for their design and ensuring that they meet the desired specifications. By utilising this approach, the design is able to effectively filter out unwanted frequencies and maintain a high level of signal quality. The resonating antenna complements the filters, enabling the system to transmit and receive signals with greater efficiency and accuracy (Zobaa and Abdel Aleem, 2021, Ram et al., 2022). The g-values were used to obtain the coupling coefficient (M) and the input/output quality factors (Qex). These parameters play a critical role in determining the performance of the filters, as they directly impact their ability to effectively filter out unwanted frequencies and maintain signal quality. By carefully selecting the appropriate values for these factors, the design is able to achieve a high degree of precision and reliability using equation (3.17) and (3.18) respectively (Carr, 2000). The width (W) and the length (L) of the patch antenna are calculated using equation (3.19) and (3.20) (Borichev et al., 2011). The antenna (a rectangular patch design in this case), possesses a dual-mode response at 1.8 GHz and 2.4 GHz depending on the feeding position used.

$$M_{n,n+1} = \frac{FBW}{\sqrt{g_1 g_2}} \tag{3.17}$$

$$Q_{ex} = \frac{g_0 g_1}{FBW} = 21.29 \tag{3.18}$$

$$W = \frac{C_0}{2f_0\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{3.19}$$

$$L_{eff} = \frac{C_0}{2f_0\sqrt{\varepsilon_{eff}}} - 2\Delta l \tag{3.20}$$

where ε_r is the dielectric constant, C_o is the speed of light in free space and L_{eff} is the effective length of the resonant element, ε_{eff} is the effective dielectric constant, and Δl is the line extension and expressed as:

$$\Delta l = 0.412h\left[\frac{0.262+\frac{W}{h}}{0.813+\frac{W}{h}}\right]\left[\frac{\varepsilon_{eff}+0.3}{\varepsilon_{eff}-0.258}\right] \tag{3.21}$$

In order to maintain the filtering characteristics of the filters, it is essential to ensure that the radiation quality factor of the patch antenna is equal to the external quality factor at the filter input. By doing so, the patch antenna's radiated power, or gain response, exhibits a pattern that closely resembles the insertion loss response of the filter. This results in a minimal insertion loss response within the passband, which corresponds to a high gain, and a substantial rejection in the off-band, translating to a low gain.

In this innovative design, a rectangular patch antenna is employed to replace the third resonator of the filters, with the ultimate objective of accommodating the requirements of a duplexing antenna system. This approach is consistent with the methodology used in the lumped element circuit model. Through this implementation, the core concept of the design remains intact, while offering an elegant and effective solution to meet the demands of the intended application.

In conclusion, the Microstrip Duplexing Antenna design, as discussed in this section, is essential to the central theme of the thesis. It exemplifies how specialised antenna design can be harnessed to meet the ambitious objectives of energy efficiency and emission reduction in the manufacturing sector, thereby contributing significantly to the journey towards net-zero manufacturing.

3.4.4 Filtering Antenna configuration

The configuration of the filtering antenna plays a critical role in the broader context of this thesis. With the focuses on the strategic utilisation of radio frequency (RF) and thermoelectric generators (TEGs) in batch manufacturing to achieve net-zero emissions, this section examines the nuanced design and practical application of filtering antennas, a key component in the efficient capture and utilisation of RF energy.

The integration of filtering antennas is essential in enhancing the performance of RF energy harvesting systems, which are a cornerstone in driving sustainable, low-carbon manufacturing processes. Filtering antennas, by design, selectively allow specific frequencies while blocking others (Yang et al.,2022). This selective frequency passage improves the signal-to-noise ratio and overall energy harvesting efficiency. Such efficiency is critical in industrial environments where multiple RF sources can cause interference and energy losses. Efficient rectification and power storage are central to the design of these antennas, focusing on whether the antenna targets ambient or intended RF energy sources (Sharma & Singh, 2023).

The role of the antennas aligns with energy-efficient design principles, contributing to reducing the energy footprint of manufacturing processes by optimising the use of ambient RF energy. This optimisation is in line with the overarching goal of achieving net-zero emissions in manufacturing, as effective energy harvesting contributes to a lower reliance on traditional, carbon-intensive energy sources (Elsheakh 2017, Wang et al. 2021).

Initially, an in-depth examination of the design for each channel filter incorporating the integrated antenna is conducted. This investigation is founded upon the utilisation of the orthogonal modes inherent to the rectangular patch antenna. Each distinct mode of the patch antenna will be meticulously integrated with its corresponding narrowband filter on an individual basis, thereby generating two separate filtering antenna responses that both employ the very same patch antenna.

This approach effectively demonstrates the versatility of the rectangular patch antenna, as it enables the creation of two distinct filtering responses within the context of the same antenna structure. By doing so, the underlying concept remains consistent, while simultaneously showcasing the potential for innovation and adaptability in antenna design and implementation.

To show this configuration, the 1.8 GHz three-poles hairpin filter has its third resonator replaced with the patch antenna as depicted in Figure 3.8. Figure 3.8(a) represents a traditional three-poles microstrip bandpass filter using hairpin resonators. In Figure 3.8(b), In order to maintain consistency within the design, the coupling coefficient between resonator 2 and the patch antenna is meticulously adjusted to match the coupling coefficient between resonator 2 and resonator 3 of the filter, as illustrated in Figure 3.8(a). Following the careful extraction of the coupling distance, the filtering antenna is subsequently assembled and optimised according to the desired specifications, resulting in the configuration presented in Figure 3.8(b).

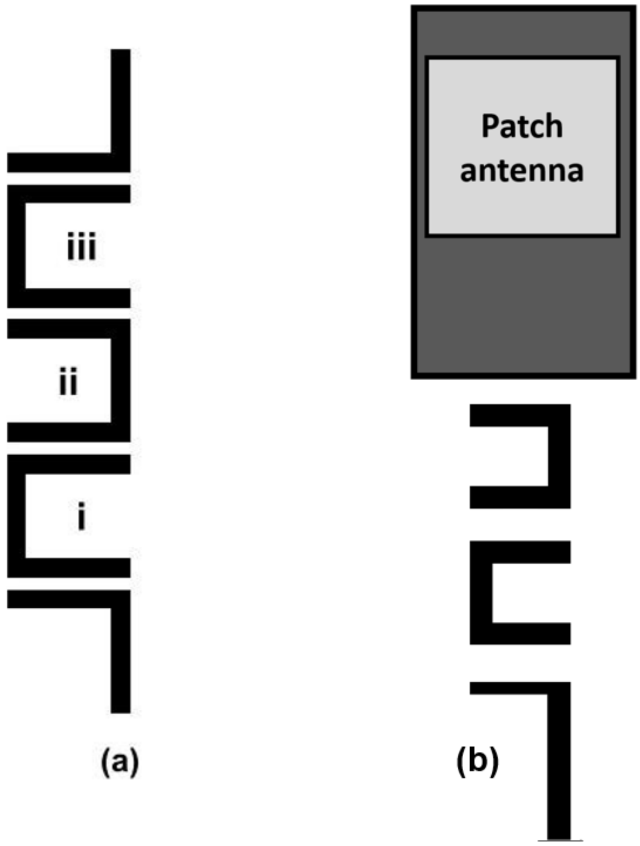

Figure 3.8 - (a) 1.8 GHz hairpin filter layout; (b) 1.8 GHz hairpin and patch filtering antenna layout.

This process ensures that the relationship between the resonators and the patch antenna remains coherent and harmonious, allowing for the effective integration of the various components. By doing so, the ultimate design is both elegant and efficient, achieving the desired performance criteria while maintaining the integrity of the underlying conceptual framework. For this element of this thesis, Sonnet is deemed an appropriate software for simulating the S-parameters of the proposed duplexing patch antenna system in order to assess its efficacy and antenna factor, as it is well-suited for analysing planar high-frequency structures (Sonnet Software, Inc., 2022). The software's accuracy and efficiency in handling complex planar structures, also make it a reliable choice for characterising antenna performance and predicting S-parameters (Microwaves101, 2023). Figure 3.9 shows the simulated response of the filtering antenna configuration after optimisation.

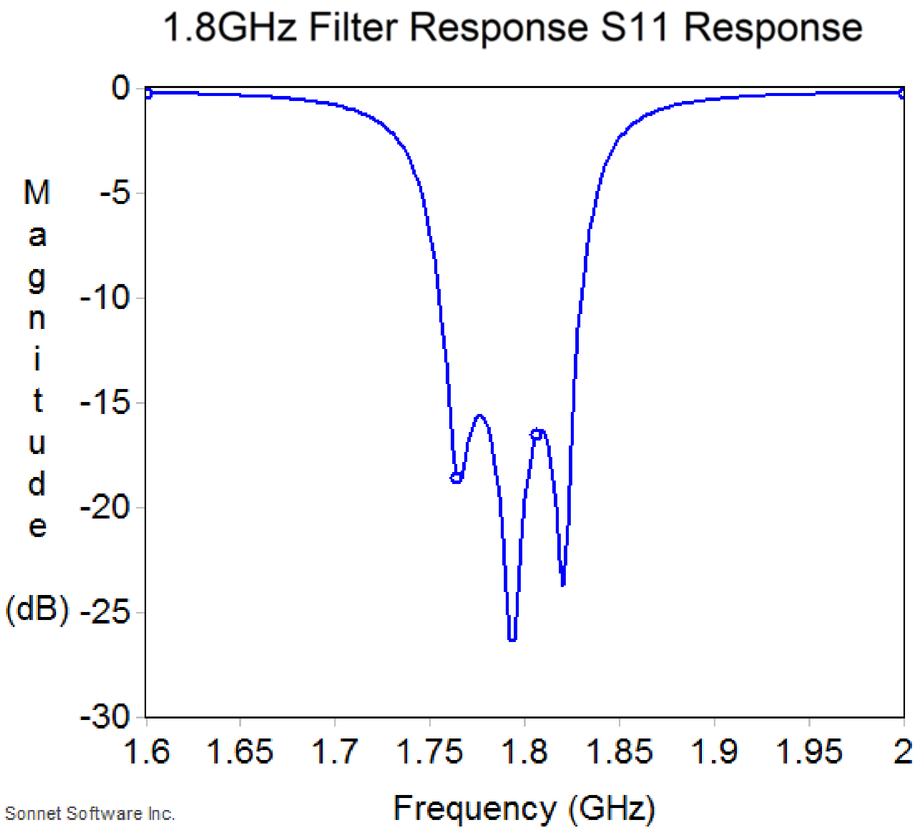

Figure 3.9 - Simulated S11 for 1.8 GHz at -10db bandwidth is 1.76GHz to 1.83GHz (or 3.8%).

Analogous procedures were employed in the development of a 2.4 GHz filtering antenna. In this instance, the second mode (2.4 GHz) of the patch antenna is skilfully in-line coupled to a corresponding 2.4 GHz filter. This is accomplished by substituting the third resonator of the 2.4 GHz filter with the versatile patch antenna, subsequently followed by a comprehensive optimisation process.

By adhering to these procedures, the integrity of the design is preserved, ensuring seamless integration between the patch antenna and the filter. This approach not only demonstrates the adaptability of the patch antenna in various frequency ranges but also showcases the effectiveness of the methodology in producing high-quality filtering antennas that cater to specific frequency requirements. Figure 3.8(b). depicts the design topology of new finality of the 2.4 GHz filtering antenna as an insert in its simulated response. The next step is to utilise both modes of the patch antenna to combine the two filtering-antennas into a duplexing antenna.

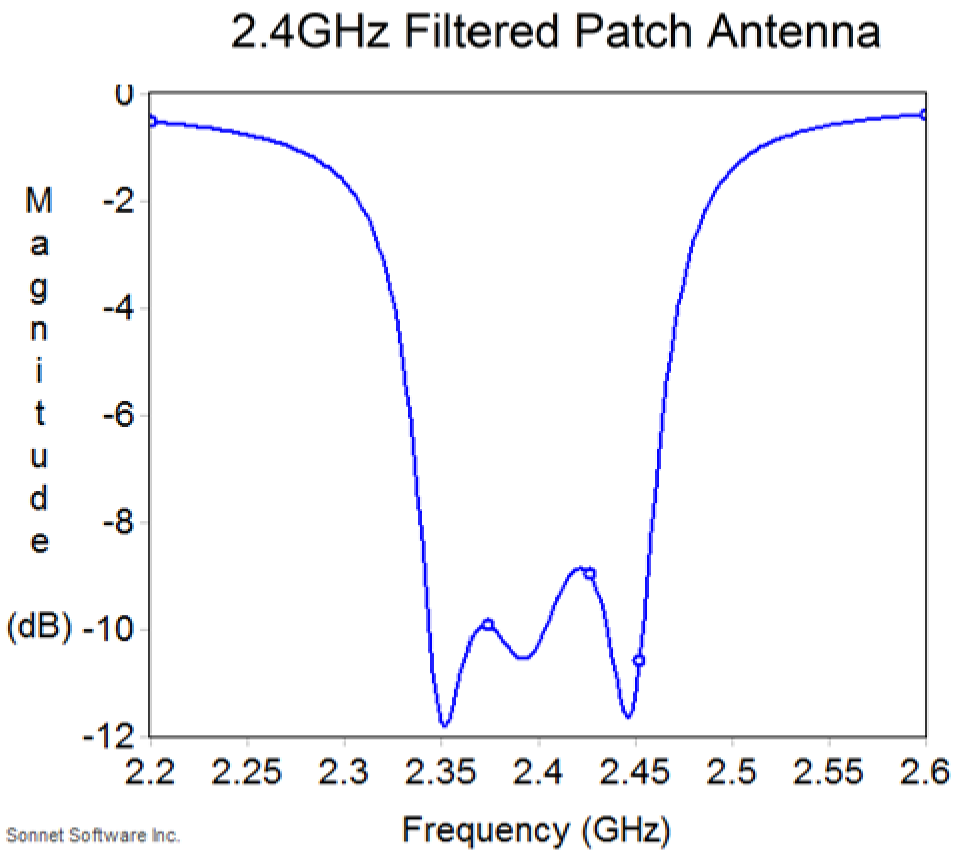

Figure 3.10 - The 2.4 GHz filtering antenna layout and simulated return loss (S11) response

The two individually tailored filters, operating at 1.8 GHz and 2.4 GHz, are meticulously integrated with an antenna to create a sophisticated duplexing antenna system. The 1.8 GHz filter fulfils the role of the receiving (Rx) channel, catering to the demands of the downlink communication process. Conversely, the 2.4 GHz filter is dedicated to serving as the transmitting (Tx) channel, effectively managing the uplink communication requirements.

This innovative integration of the two distinct filters with a single antenna structure enables the efficient handling of both the receiving and transmitting channels within a duplexing antenna system. By doing so, the design achieves a harmonious balance between the two frequency bands, successfully addressing the unique challenges associated with managing downlink and uplink communications concurrently. Figure 3.11 presents this resulting coupling configuration of the duplexing antenna in a classic cascaded configuration design whilst Figure 3.12 presents the purported coupling topology. The proposed design (new layout) is presented in Figure 3.13 showing that the dimensional parameters have been successfully attained. The design prototype is expertly fabricated on a Rogers RO4003C substrate, characterised by a dielectric constant of 3.55, a thickness of 1.524 mm, and a loss tangent of 0.0029 (nominal value at 10 GHz). The resulting physical dimensions achieved through optimisation are described following Figure 3.13, showcasing the successful realisation of the design.

For the fabrication process, the advanced LPKF ProtoMat S63 micro-milling technique was employed, ensuring a high degree of precision and accuracy in the execution of the prototype. This method allows for the intricate details and specifications of the design to be effectively translated into a tangible, functional prototype, demonstrating the potential of the duplexing antenna system in real-world applications.

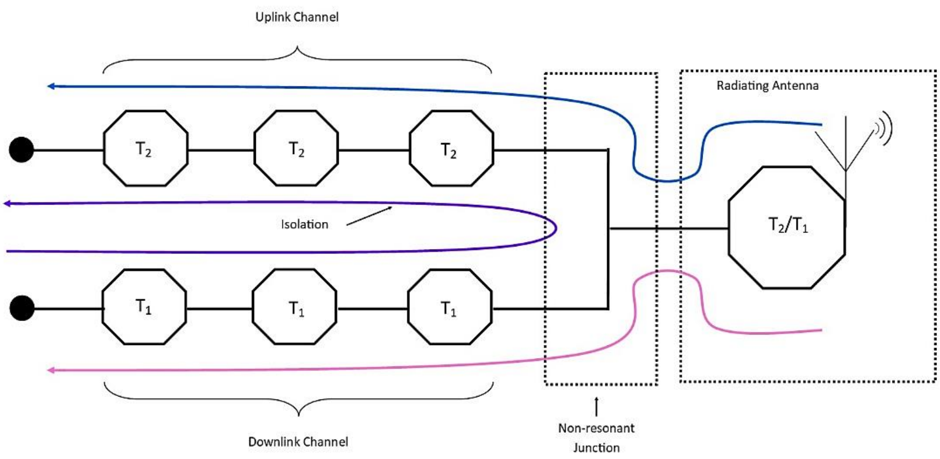

Figure 3.11 - Coupling configuration of the duplexing antenna in a conventional cascaded design

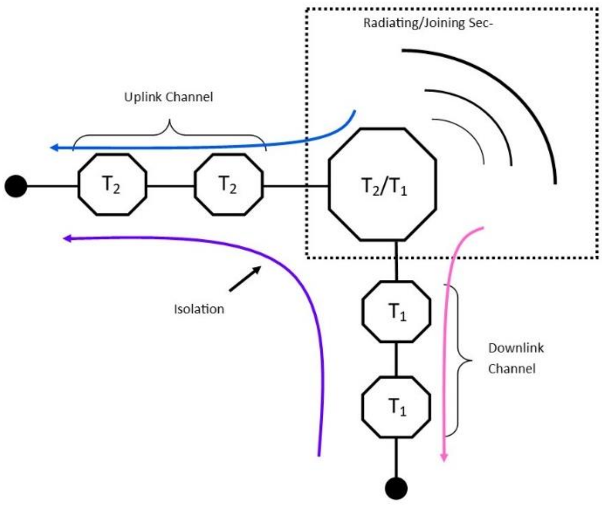

Figure 3.12 - Proposed coupling topology

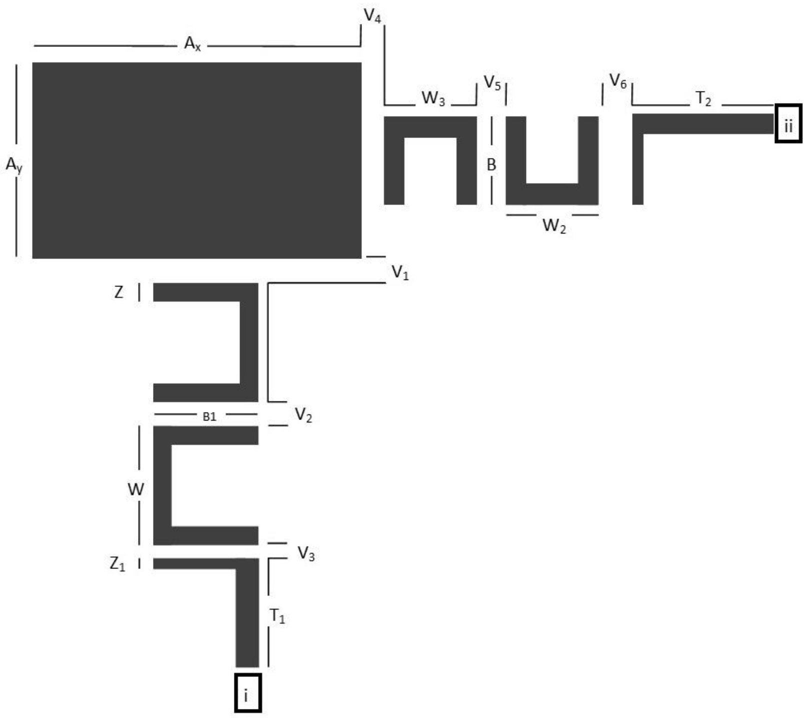

Figure 3.13 - Designed duplexing antenna layout with parameters

The parameters for the labels on Figure 3.13 are as follows: Ax = 52.5 mm, Ay = 43 mm, V1 = 1.05 mm, V2 = 2.1 mm, V3 = 0.3 mm, V4 = 0.25, V5 = 2 mm, V6 = 0.3 mm, T1 = 15 mm, T2 = 20 mm, H = 15.5 mm, B1 = 17.9 mm

The simulated S-parameters of the optimised duplexing antenna are elegantly showcased in Figure 3.14, which highlights the receiving (Rx) channel spanning from 1.764 GHz to 1.836 GHz, and the transmitting (Tx) channel ranging from 2.352 GHz to 2.448 GHz. The displayed responses demonstrate that the design achieves a useful bandwidth for the 2.4GHz band while the 1.8GHz response is rather narrow band and a subsequent iteration of the design could revise the filter to achieve a wider bandwidth. Furthermore, the sharp skirts commonly observed in co-designed filtering antenna responses are prominently visible in both channels, indicating a well-executed design.

The return losses are measured at -17 dB and -13 dB, respectively, for the two channels. Additionally, the isolation between the two channels (ports S21) is approximately -51 dB for the Rx channel and -43 dB for the Tx channel. As illustrated in

Figure 3.14, the isolation S21, when compared with S11 and S22, reveals an impressive degree of isolation between the channels. Moreover, it can be observed that the three poles for each channel are distinctly discernible, which signifies the critical contribution of the antenna as a resonant pole for both the Rx and Tx channels. This further underscores the effectiveness and precision of the duplexing antenna design.

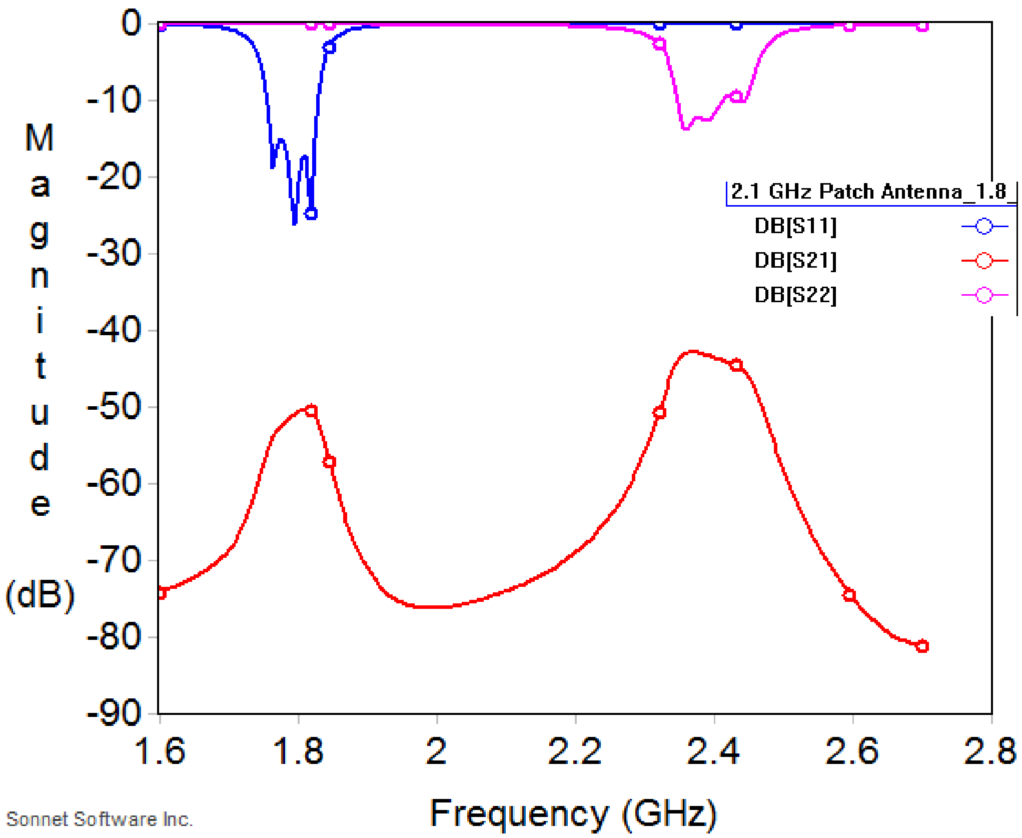

Figure 3.14 - Simulated duplexer antenna isolation between two channels (ports) and the frequency responses

Figure 3.15 to Figure 3.17 showcase the assessed far-field radiation patterns for both co- and cross-polarizations at frequencies of 1.8 GHz and 2.4 GHz, presenting valuable insights into the performance of the advanced duplexing antenna design proposed in recent research (Kraus & Marhefka, 2002; Balanis, 2016). Impressively, the peak directivity or maximum far-field signal strength achieved using this state-of-the-art duplexing antenna configuration for the E-plane at 1.8 GHz (cross-polarization) and the E-plane at 2.4 GHz (co-polarization) indicates a significant margin of approximately -53 dB at zero degrees. This observation underscores the vital role (Kraus & Marhefka, 2002; Balanis, 2016) played by the antenna as a resonant pole for each unique channel.

Through the careful analysis of these radiation patterns, it becomes evident that the duplexing antenna design offers a high level of precision and efficiency, successfully accommodating the unique requirements of both the receiving and transmitting channels (Tx and Rx). Furthermore, the polarization isolation between the cross-polarization and co-polarization is about 22 dB at an azimuth angle of zero degree as shown in Figure 3.15. Whilst the measured far-field radiation patterns at the H-plane for both co-polarization at 1.8 GHz and cross-polarization at 2.4 GHz results in undesirable radiation patterns with noticeable polarization isolation around 320 degrees as highlighted in Figure 3.16 and Figure 3.17 with the likelihood of reduced performance. In addition to this undesirable radiation pattern, it has been reported that orthogonal mode patch antenna is not applicable in real world as it only functions in one mode (channel). Because of this, this designed duplexing antenna is limited to operate effectively in the WIFI (2.4 GHz) application or in the Tx channel. This none-functioning in real world is noticed during the RF energy harvesting using this designed Duplexing antenna and is explained further in the RF energy harvesting section of this report. It is assumed that the discrepancies noticed in the far-field radiation patterns of Figure 3.15 to Figure 3.17, as well as S-parameters of

Figure 3.14 are associated with fabrication tolerance, post fabrication tunning, and the variation of the dielectric constant for the high permittivity dielectric material of Rogers RO3004C.

To mitigate the discrepancies observed in the far-field radiation patterns and S-parameters, as highlighted in Figures 3.14 to 3.17, employing improved fabrication accuracy (Balanis, 2016), advanced design methods like simulation and optimisation (Pozar, 2011), and intricate attention being paid to material characterisation with potential exploration of alternative materials (Wong, 2003) could prove essential in enhancing system accuracy and reliability. The significance of accurately characterising the dielectric materials. The Rogers RO3004C, used in this fabrication is optimally stable for this build application. It is known that variations in the dielectric constant (in other substrates) can be significant.

The exploration and implementation of filtering antenna configurations in this section not only aligns with the objectives of this thesis but also contributes to the field of sustainable manufacturing practices. These configurations enhance the efficiency of RF energy harvesting systems, thereby supporting the broader goal of sustainable and energy-efficient manufacturing

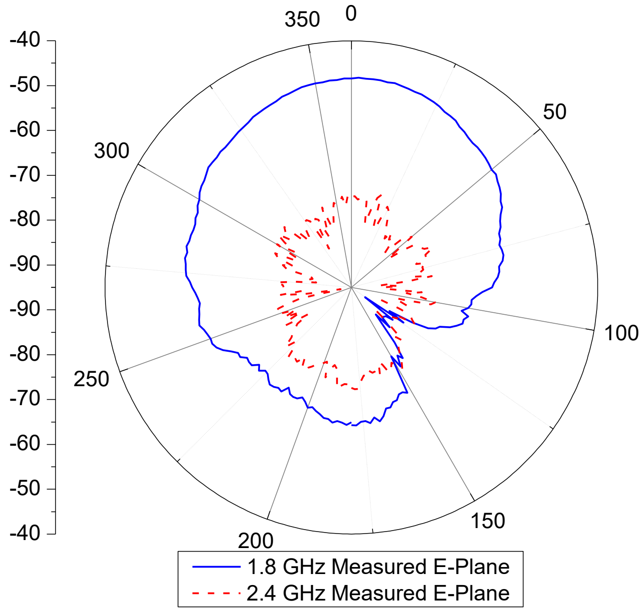

Figure 3.15 - Measured far-field radiation patterns on the E-plane at 1.8 GHz (cross-pol) and 2.4 GHz (co-pol)

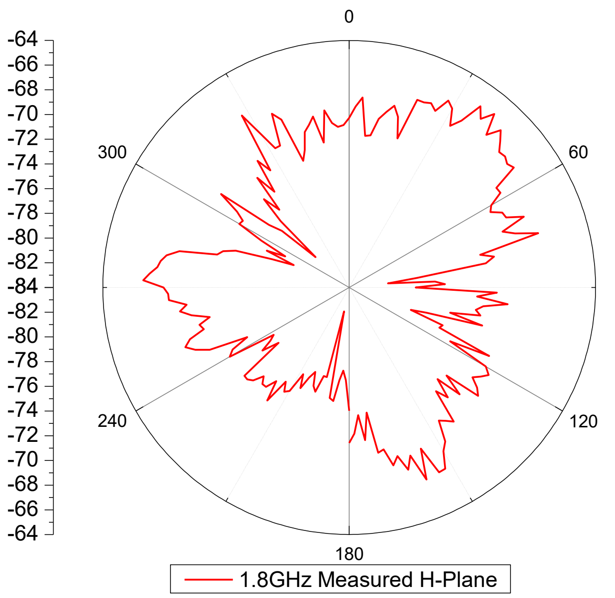

Figure 3.16 - Measured far-field radiation patterns on the H-plane at 1.8 GHz (Co-pol)

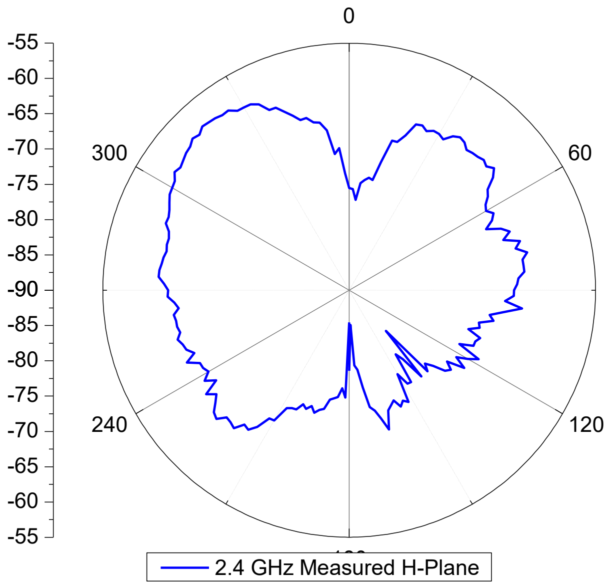

Figure 3.17 - Measured far-field radiation patterns on the H-plane at 2.4 GHz (cross-pol)

3.5 Experimentation, calibration, and benchmarking (testing in a typical manufacturing environment)

After a thorough analysis of the literature review and subsequent build of RF harvesting antenna, this section details the process of validating the efficacy of the designed antennas. This section also considers the elements of a typical manufacturing environment and its effects on the ability/inability to harvest radio frequencies in order to gain useful energy towards a net zero GHG implementation. The process of calibration is thus also discussed within.

Figure 3.18 to Figure 3.24 depict the initial setup and running of the exploratory trials.

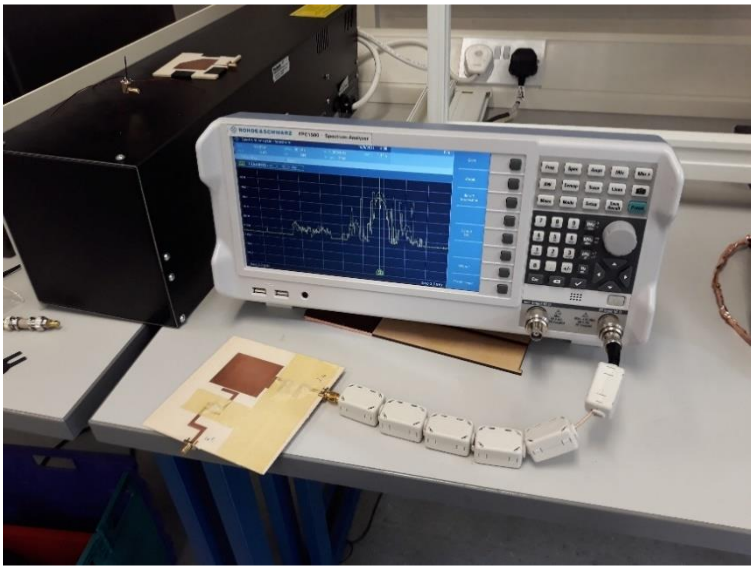

Figure 3.18 - Measurement of RF signal level in Electronics laboratory from Patch Antenna via Spectrum Analyser. Ferrite clamps to reduce stray signals coupled into the coax cable

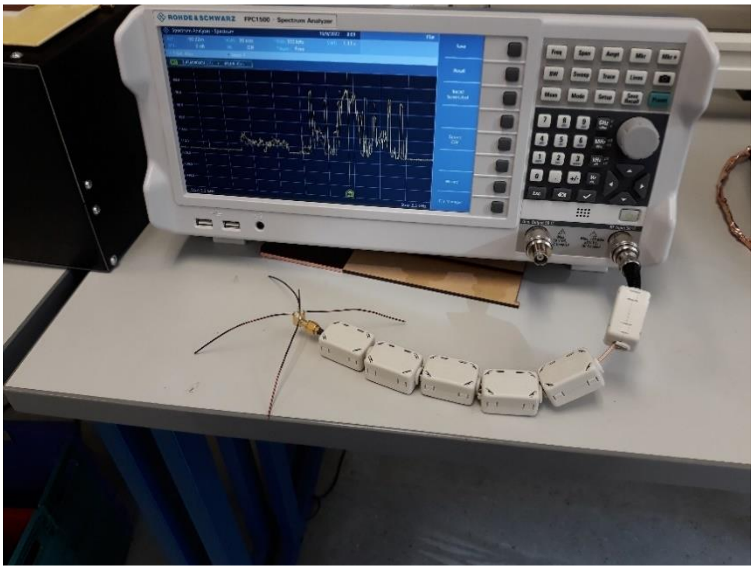

Figure 3.19 - Measurement of RF signal level in Electronics laboratory from ¼ Wave Antenna via Spectrum Analyser

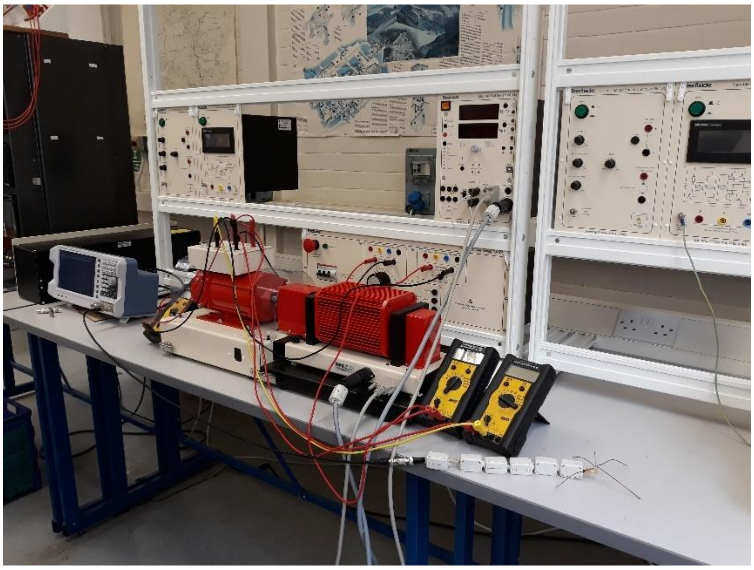

Figure 3.20 - Measurement of RF signal level from ¼ Wave Antenna via Spectrum Analyser – with motor test rig operating

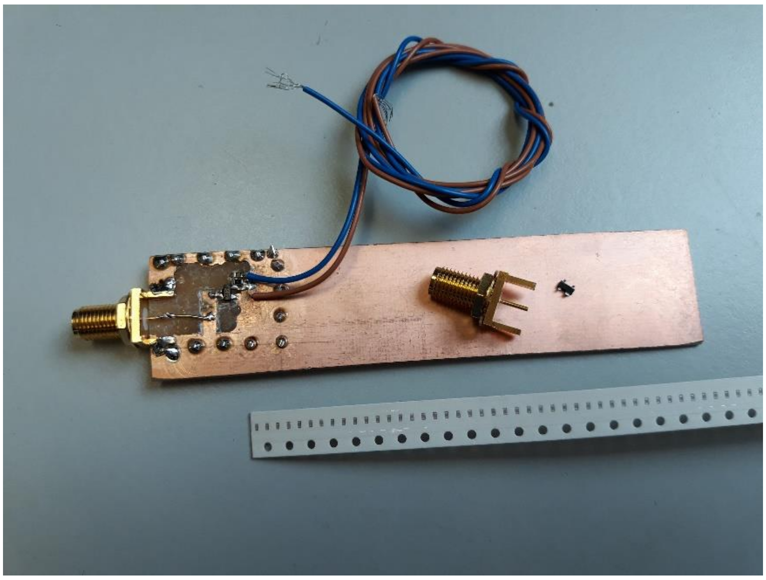

Figure 3.21 - Layout of RF rectifier board. SMA connector and rectifier diode placed on the blank area to indicate sizes

Figure 3.22 - Measurement of RF signal level in Electronics laboratory from Log Periodic via Spectrum Analyser. Polarization is Horizontal

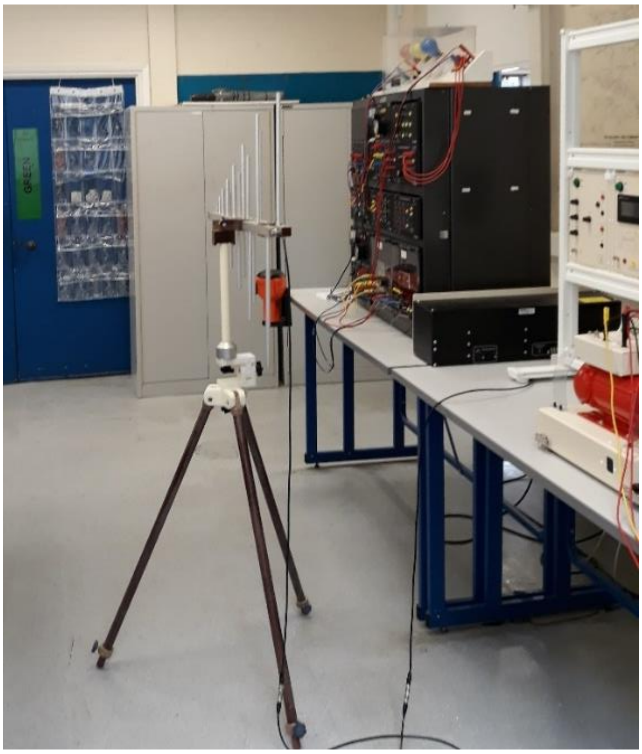

Figure 3.23 - Measurement of RF signal level in Electronics laboratory from Log Periodic via Spectrum Analyser. Polarization is Vertical

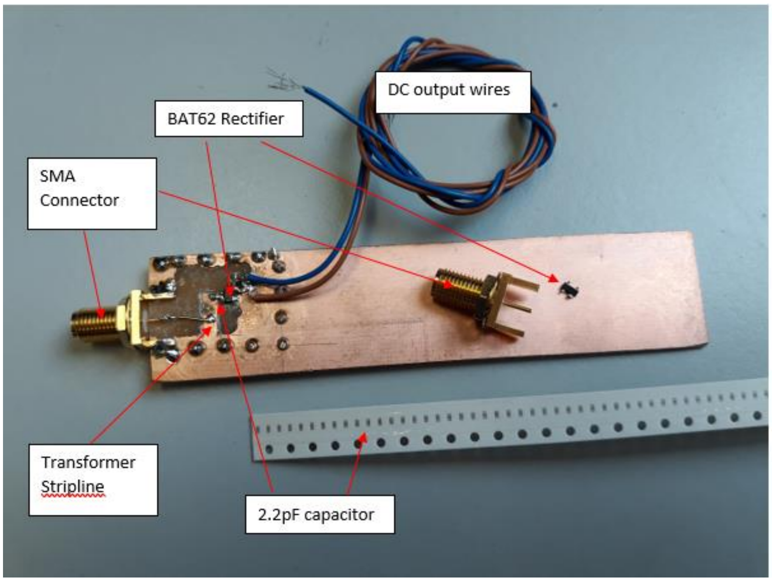

Figure 3.24 - Layout of RF rectifier board, component locations are detailed

The trial run is to show the relative sensitivity of a group of antennas to Wi-Fi signals within the 2.0 GHz to 2.5 GHz region. The signal source is a ceiling mounted Wi-fi router (model Aruba 303 series AP). The unit will typically transmit 2.4Ghz to an upper transmission frequency of 5 GHz, in the dual-band operation - including both 2.4 GHz and 5 GHz frequency bands (Aruba Networks, 2023). and is built for indoor use to establish communication with devices such as phones or laptops/desktop. It must be noted that these tests are carried out within a semi-controlled environment of the Electronics Laboratory and again within the school of engineering machine shop. Where the latter is an active workshop and should depict what a typical batch manufacturing environment will look like (both with layout and the use of machinery that have the ability to generate emissions within the frequency being studied) The spectrum analyser, Rohde & Schwarzis set to measure the RMS signal, the initial setup being with a “max hold” trace. This displays the maximum RMS level across the band after a few minutes.

Equation (3.22) is the calculation of the power value (in W) from a given dBm value.

$$P\,(W) = 1\,W\,x\,\frac{10^{\left(\frac{P(dBm)}{10}\right)}}{1000} \tag{3.22}$$

Decibel-milliwatts, commonly denoted as dBm, is a dimensionless unit employed for the purpose of defining and measuring signal strength or power levels, utilizing a reference point of 1 milliwatt. In other words, a power level of 0 dBm corresponds to 1 milliwatt. The dBm unit is particularly convenient and versatile, finding widespread use across various fields such as radio, microwave, audio applications, and fibre-optic communication networks for the quantification of signal strength.

One of the primary advantages of expressing signal strength or power levels in dBm is the ability to represent both exceedingly large and remarkably small power values (measured in watts) using a manageable numerical range (Rappaport, 2002; Sklar, 2001). For example, 5 milliwatts can be expressed as 7 dBm, while 100 kilowatts can be denoted as 80 dBm. Furthermore, the decibel unit greatly simplifies mathematical operations, transforming the otherwise complex processes of multiplication and division into more straightforward addition and subtraction procedures. This convenience and efficiency make dBm an invaluable tool for conveying signal strength across various applications and industries (Rappaport, 2002; Sklar, 2001).

With this understanding of the importance of the dBm scale, consider the noise baseline of the spectrum analyser, which lies between -115 and -114 dBm. In the case where the cable is terminated with a 50-ohm RF terminator, peaks are measured from 2.429 GHz to 2.443 GHz, and (2.457, 2.462 to 2.464, 2.468 to 2.472) at -102 to -88.7 dBm (Rappaport, 2002; Sklar, 2001). These measurements demonstrate that the cable's screen is "leaking" some signal within this frequency range. By utilising dBm as a measurement unit, the analysis of such signal leakage becomes more accessible and comprehensible, further emphasizing its value in various applications and industries.

The plot shows the response of the ¼ wavelength antenna to the WIFI signals. The highest levels detected are in the range -73 to -66 dBm. In the context of energy harvesting, the available voltage is of interest as that determines whether there is enough signal to allow rectification via simple diodes. In this case, -66 dBm RMS corresponds to only 0.159mV peak signal.

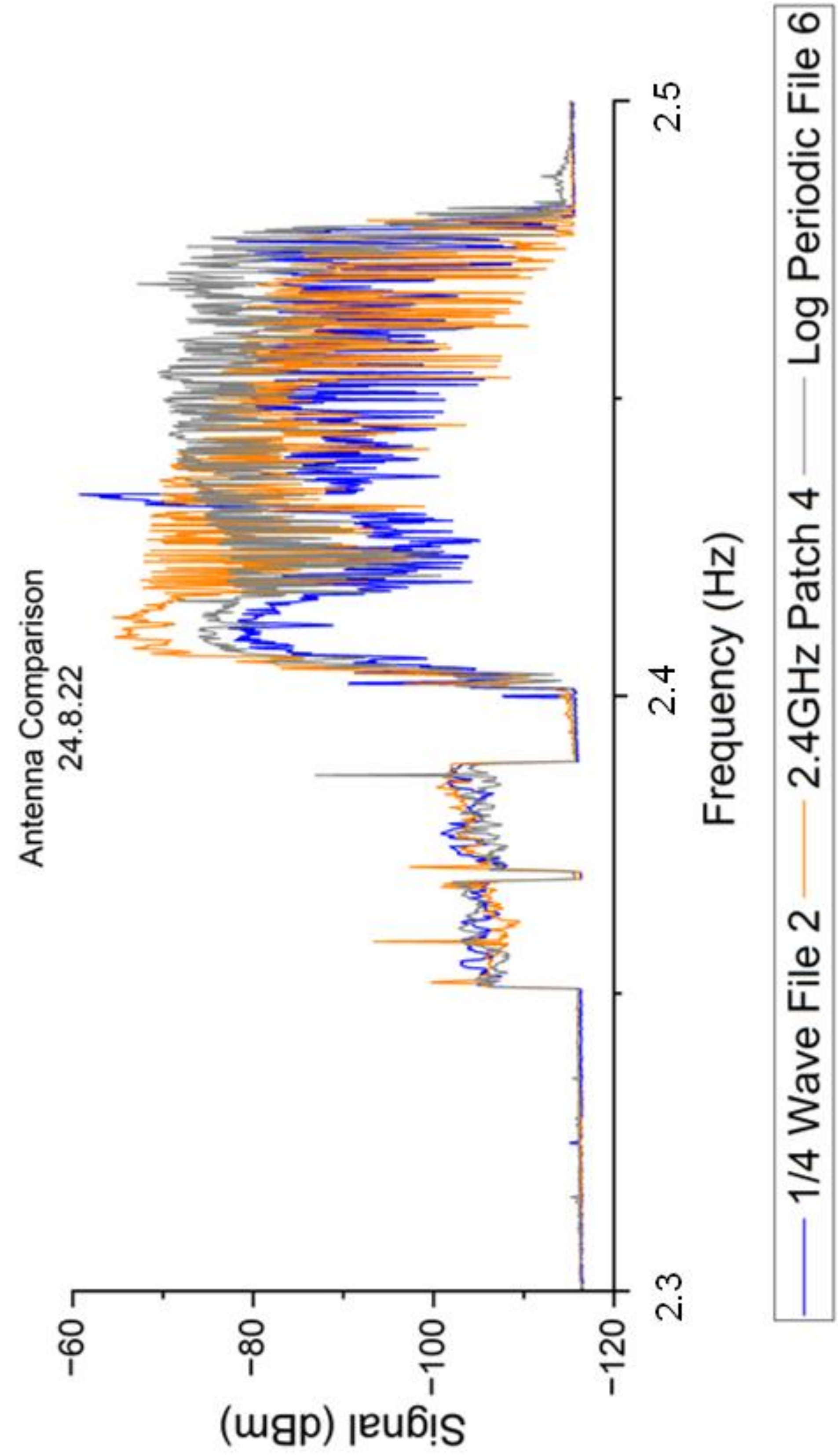

Figure 3.25 - Response of ¼ wavelength antenna to WIFI signals

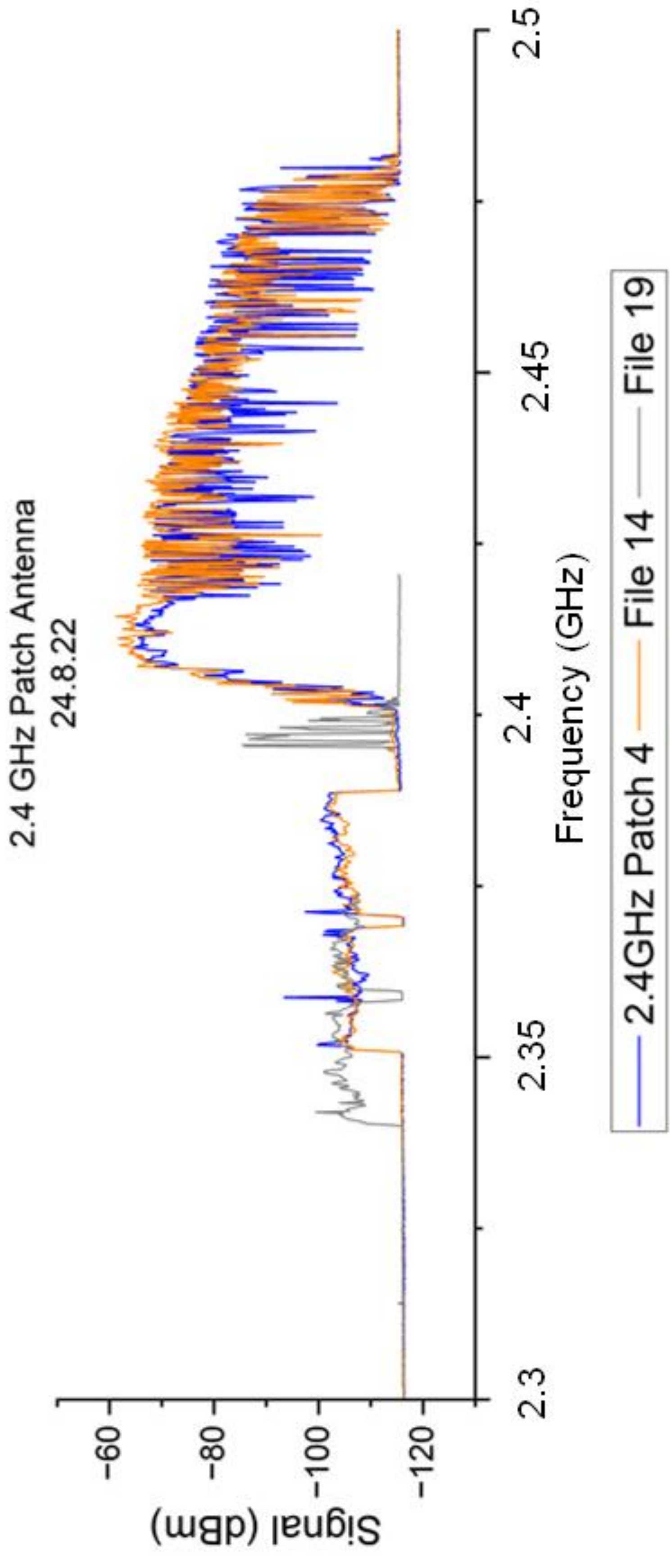

Figure 3.26 - Tx of duplexing antenna; response through 2.4 GHz patch antenna

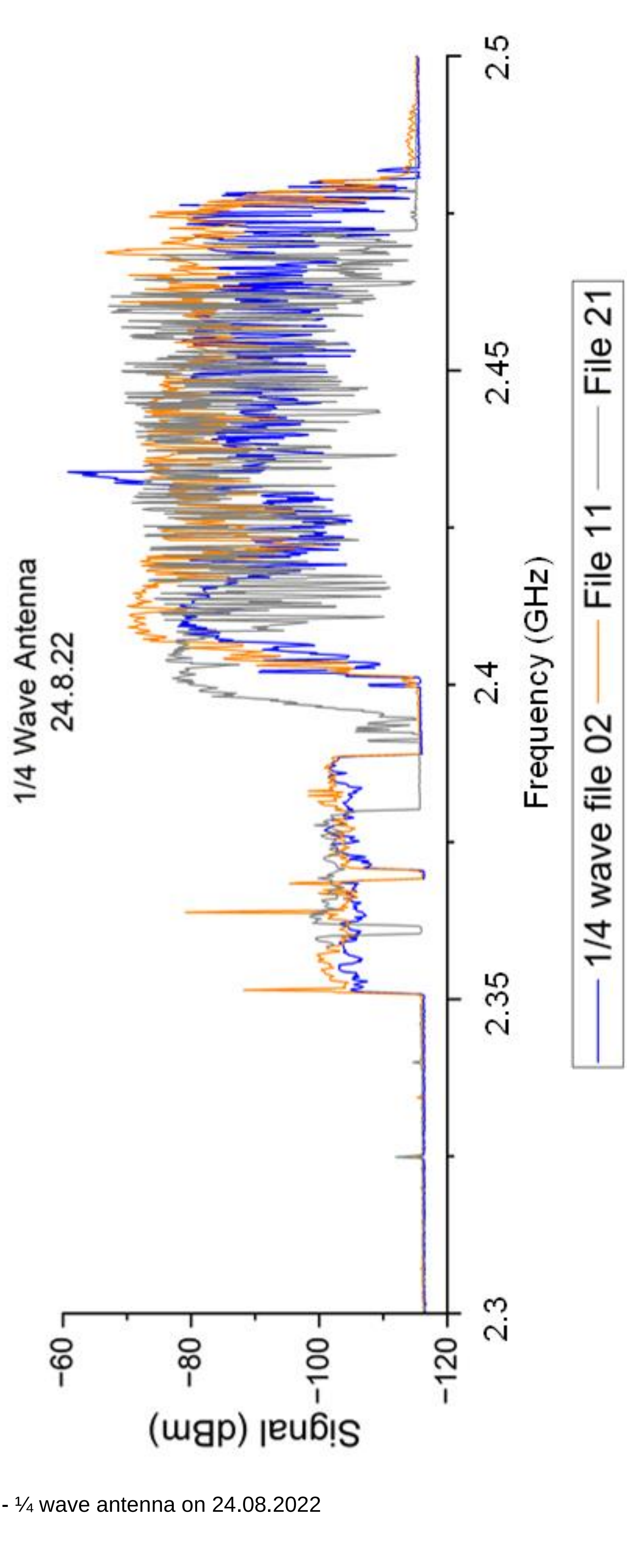

Figure 3.27 - ¼ wave antenna on 24.08.2022

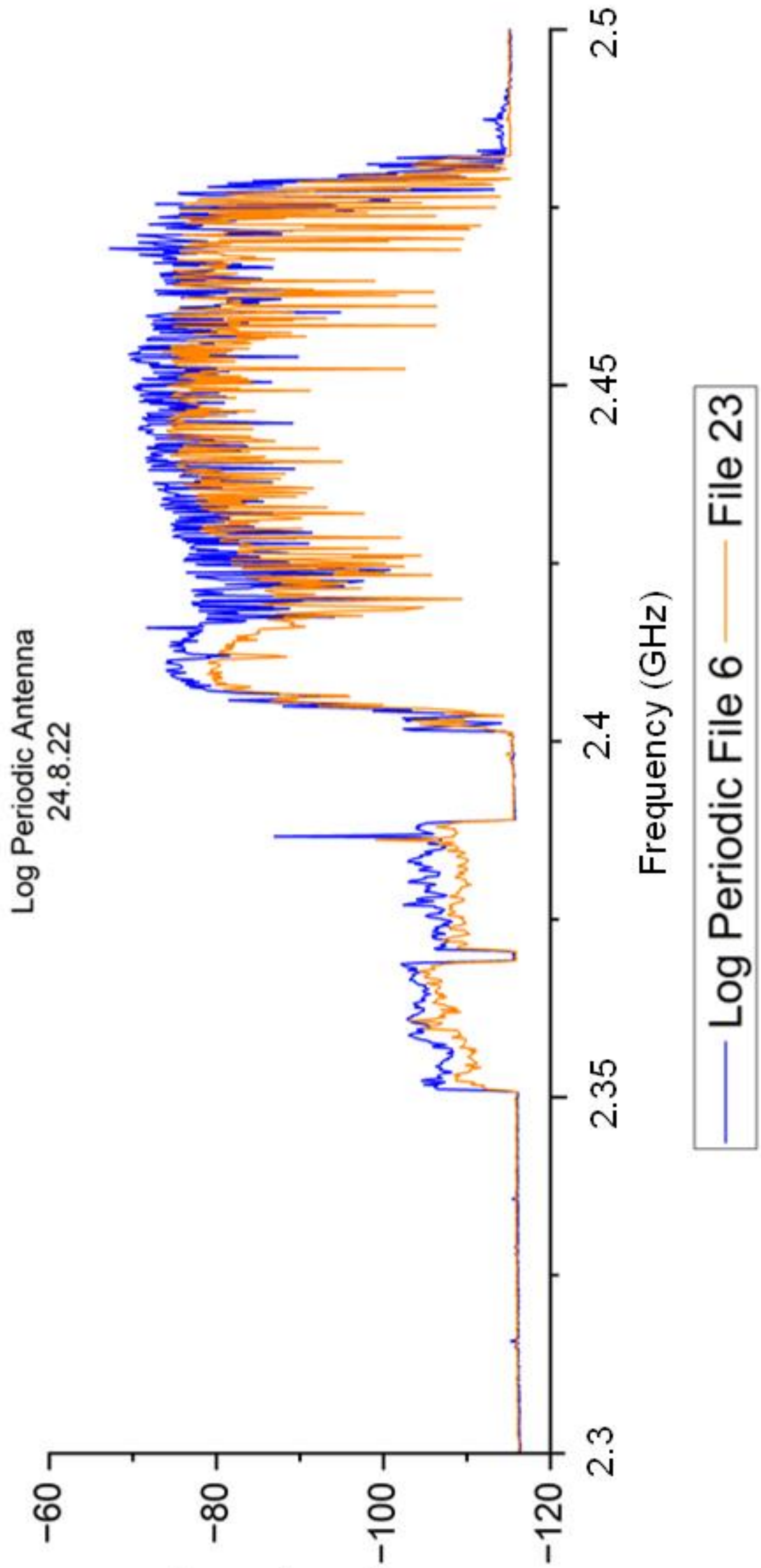

Figure 3.28 - Log periodic antenna on 24.08.2022

The Tx of the Duplexing antenna channel trace shows the response through the 2.4GHz patch antenna. Bearing in mind that the TX channel alone is a filtering antenna with 4% Fractional bandwidth. This Tx channel gave a signal level around -69 dBm at 2.436 GHz which is similar to that of the ¼ wave-length antenna. The signals observed suggest that the bandwidth is narrower than the ¼ wave antenna.

The test with the AC motor test set was to show how much RF energy in the 2.4GHz band was detected from a 70W electric motor driving a dynamometer using a closed loop constant torque control. The test arrangement used an extra BNC cable (1m long) and this showed another “leakage” peak at 2.406 GHz.

The signals from the Wifi are lower, peaks around -73 dBm. In this context, the peaks are not of interest. The gaps where the Wifi falls to the noise level are the regions where any significant noise from the AC motor system would be observable. In any electrical system that exhibits dissipative characteristics, there exists an inherent generation of electrical noise, which stems from the finite thermal excitation experienced by electrons (Nyquist, 1928). This noise bears a striking resemblance to the blackbody emissions that are produced by objects maintained at a specific temperature, as both share a comparable frequency spectrum (Planck, 1901).

At typical operational temperatures, the apex of these emissions is situated in the mid-infrared range, which lies significantly above the frequencies that concern us in the context of microwave applications (Pozar, 2011). Consequently, it is feasible to consider the noise generated in such scenarios as independent of frequency.

In relation to a source resistance, denoted as R, the maximum noise power is transferred to a matched load bearing the same resistance value (Johnson, 1928). Interestingly, this maximum noise power remains unaltered, regardless of the resistance value in question. This phenomenon emphasises the importance of appropriate load matching in electrical systems to optimise noise performance.

It is clear from the plot that the noise regions (B to C) show no detectable signals from the AC motor system.

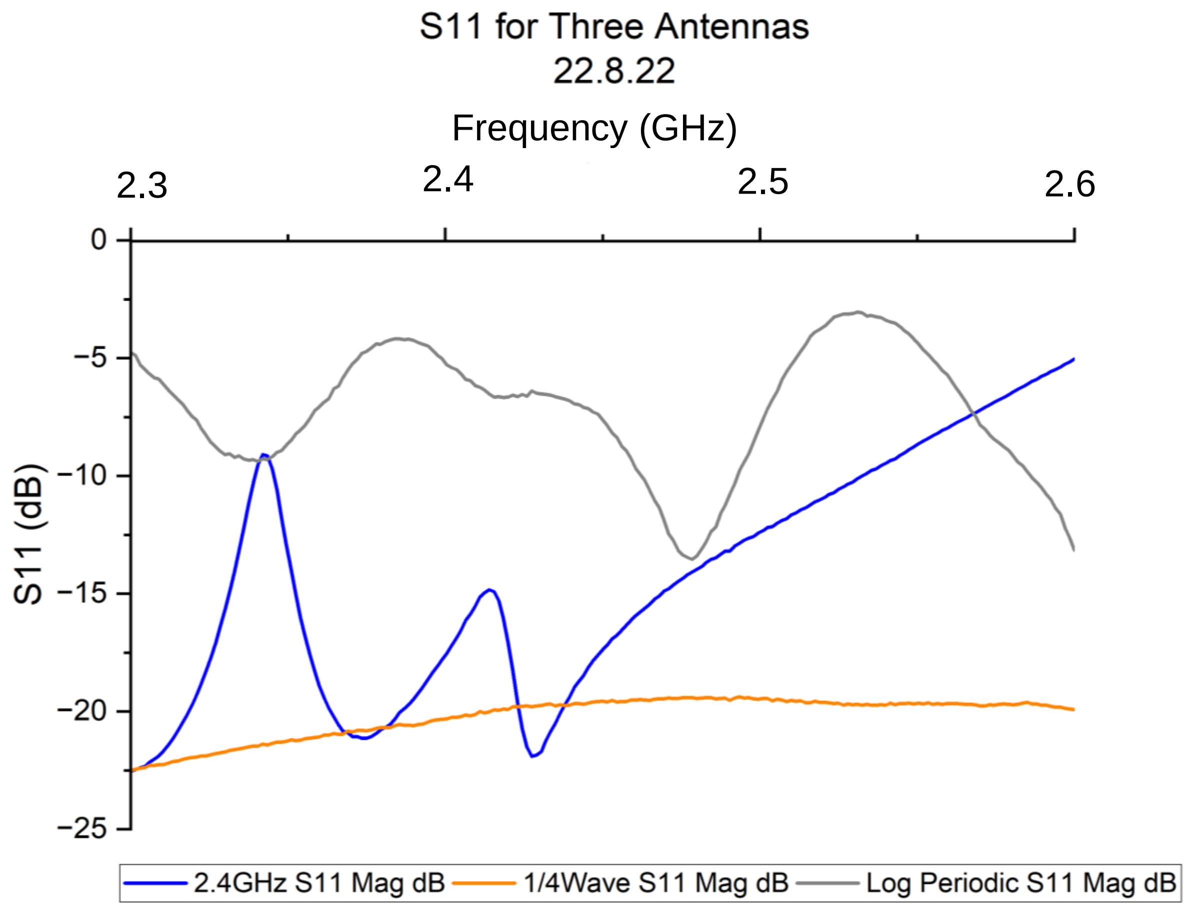

Figure 3.29 - S11 response for three antennas

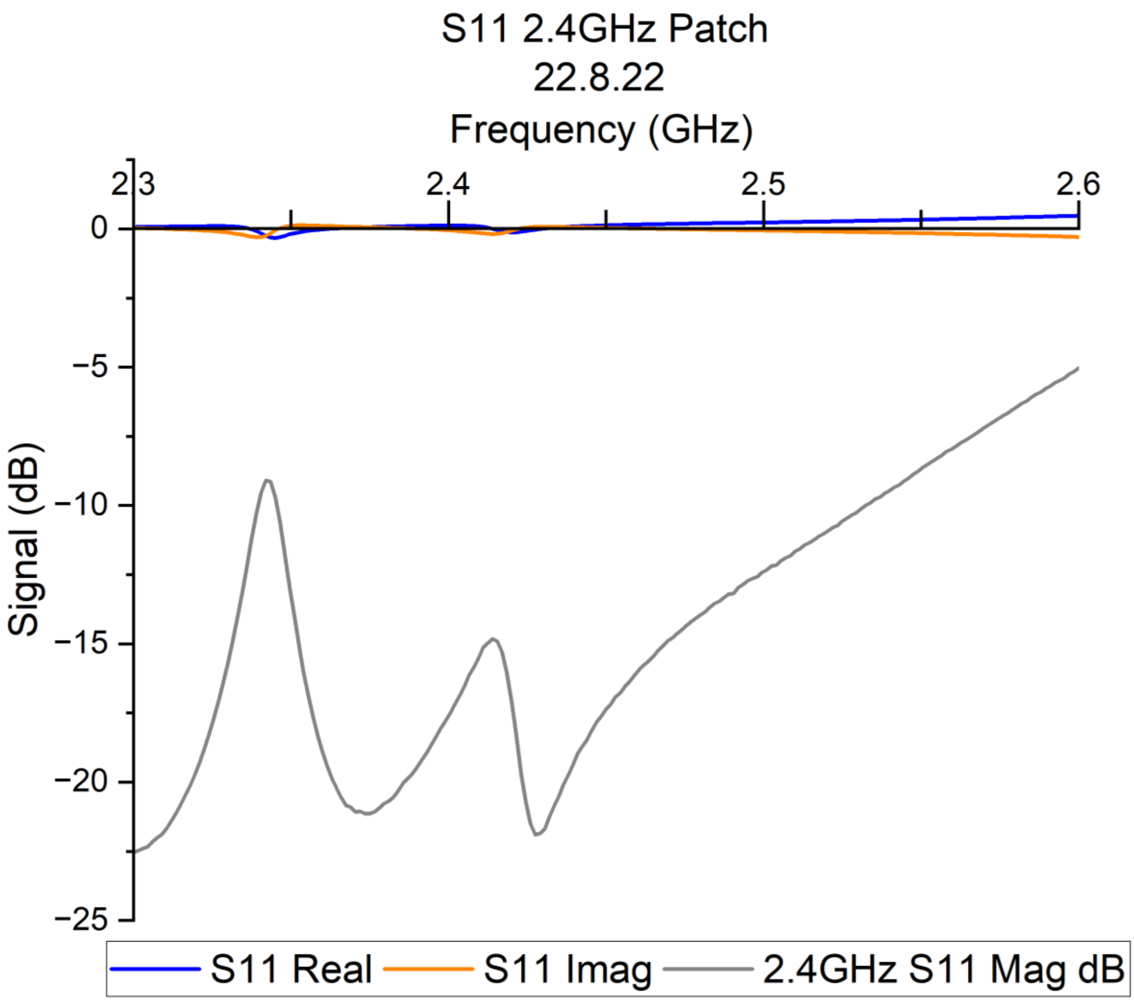

Figure 3.30 - S11 response for 2.4 GHz patch on 22.08.2022

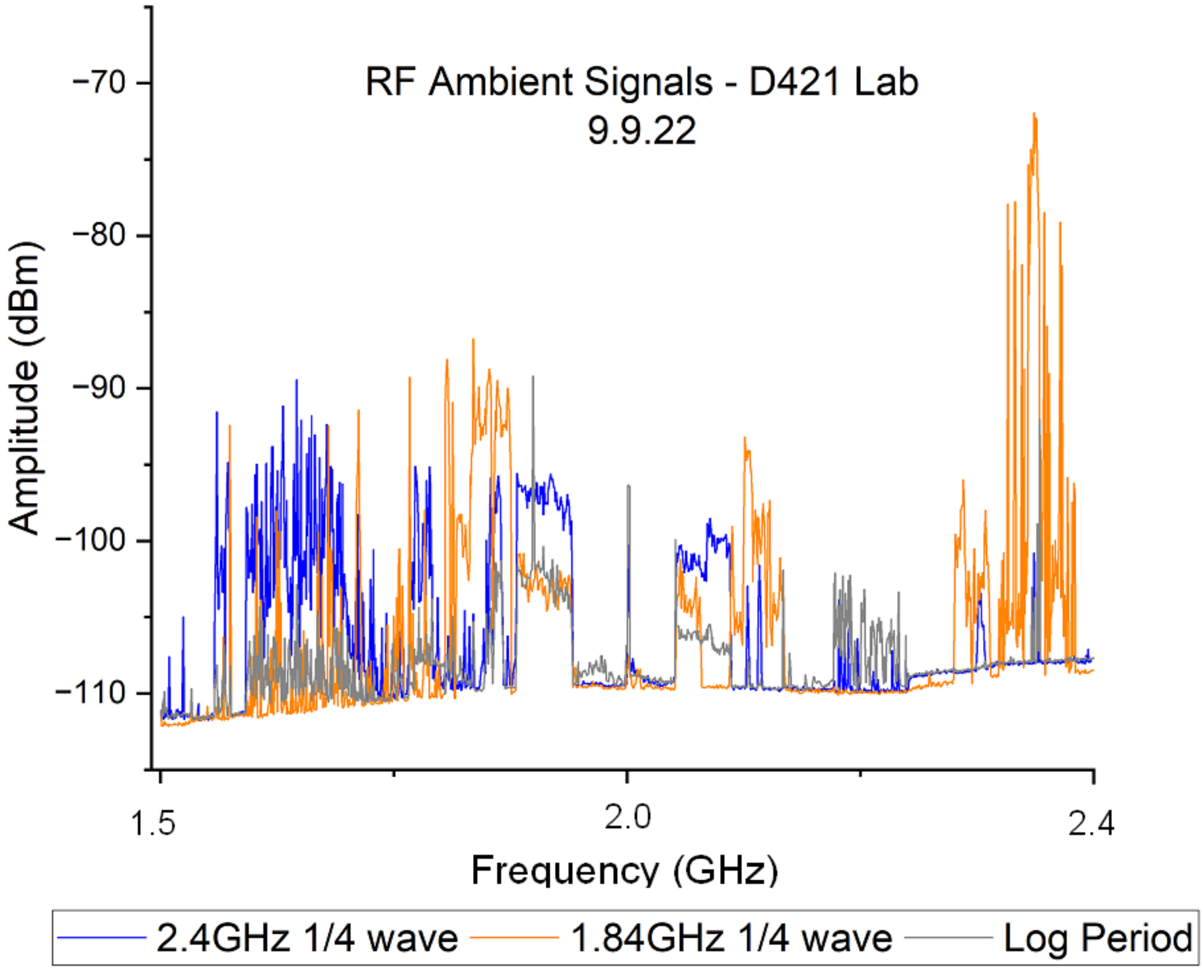

Figure 3.31 - RF ambient signals – D421 lab on 09.09.2022

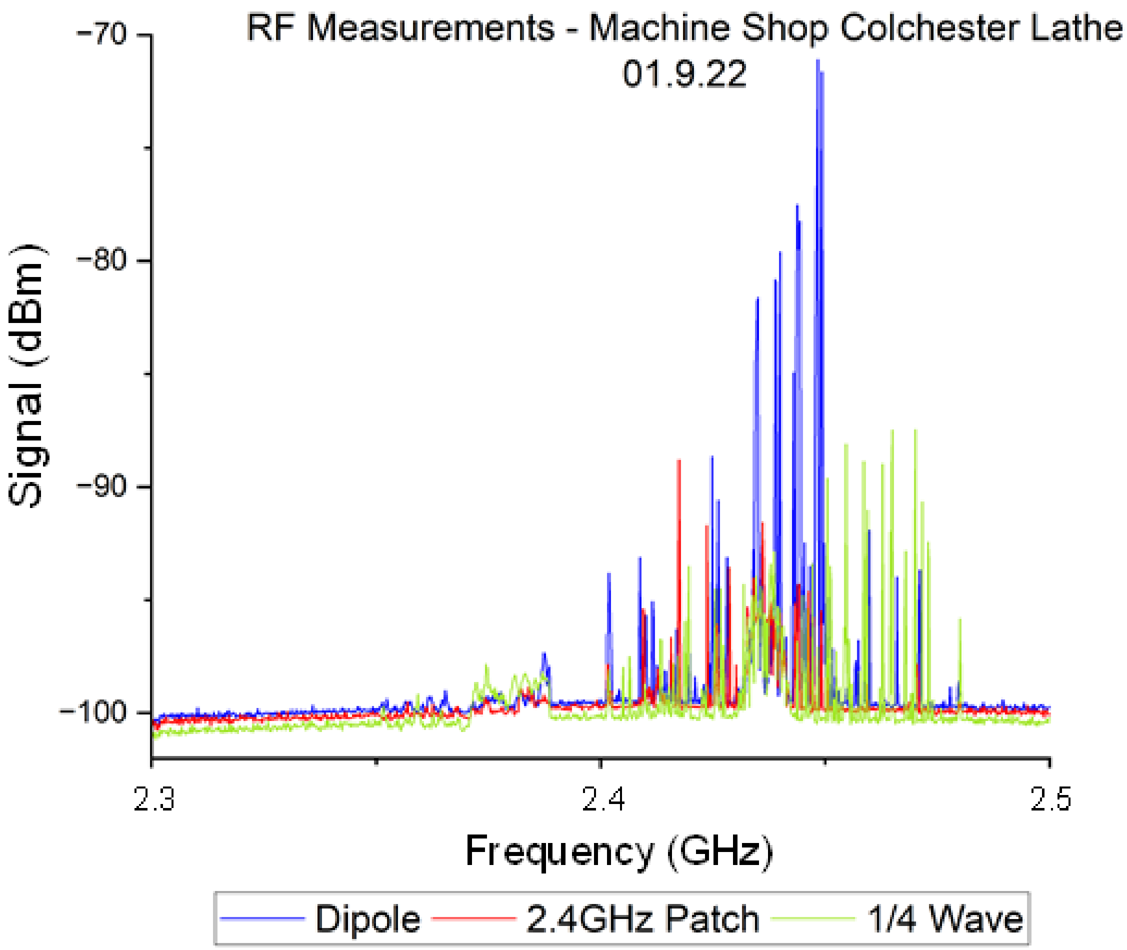

Figure 3.32 - RF measurements – machine shop Colchester lathe on 01.09.2022

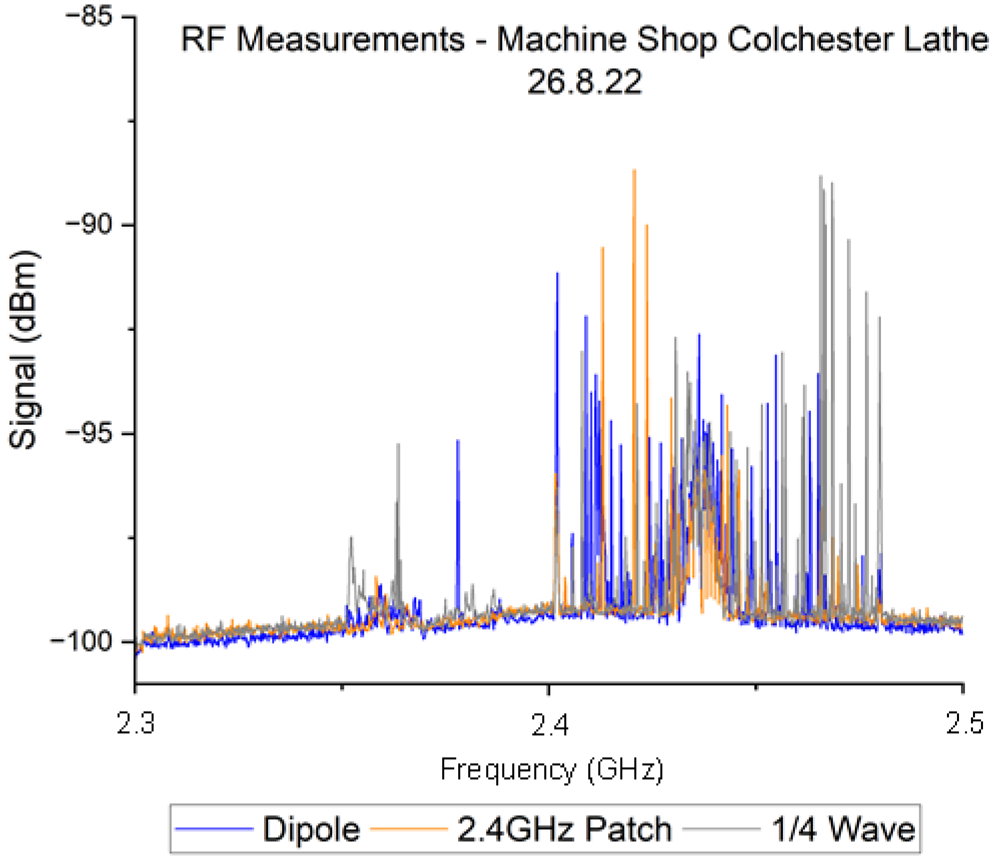

Figure 3.33 - RF measurements – machine shop Colchester lathe on 26.08.2022 (dBm)

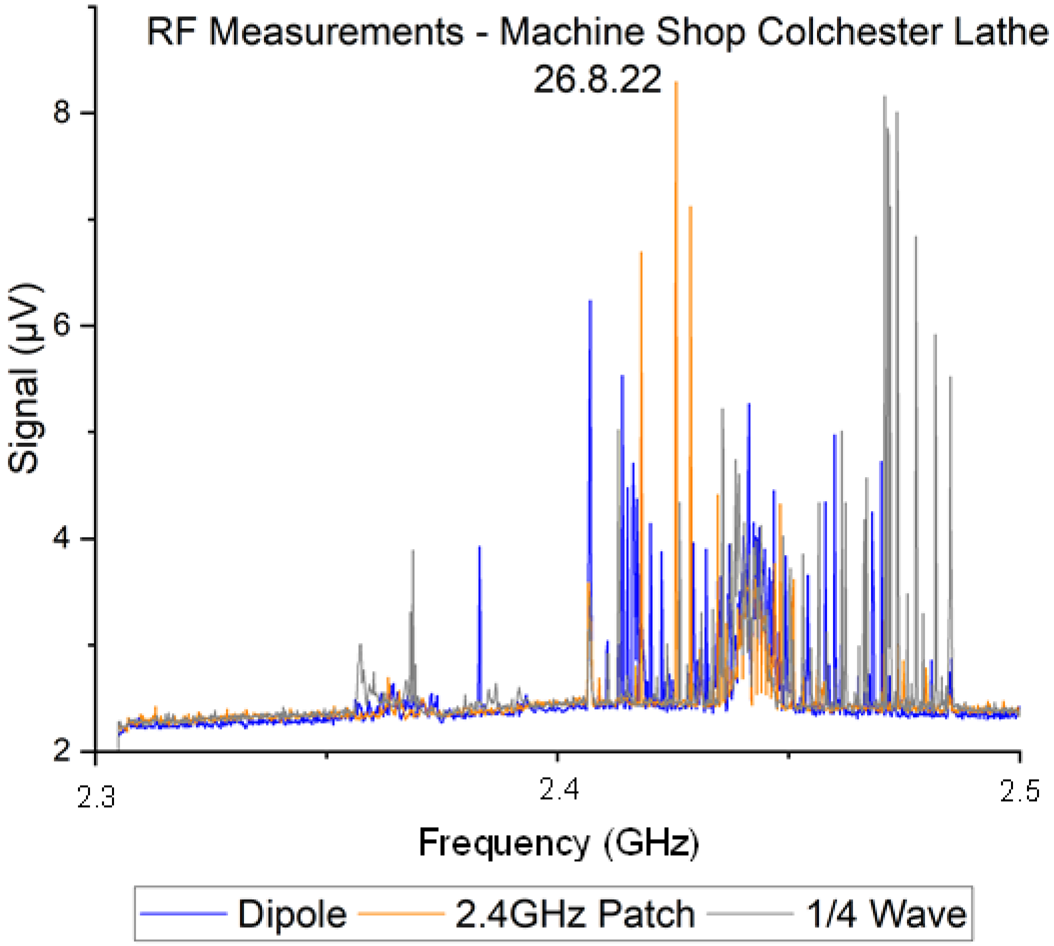

Figure 3.34 - RF measurements – machine shop Colchester lathe on 26.08.2022 (microV)

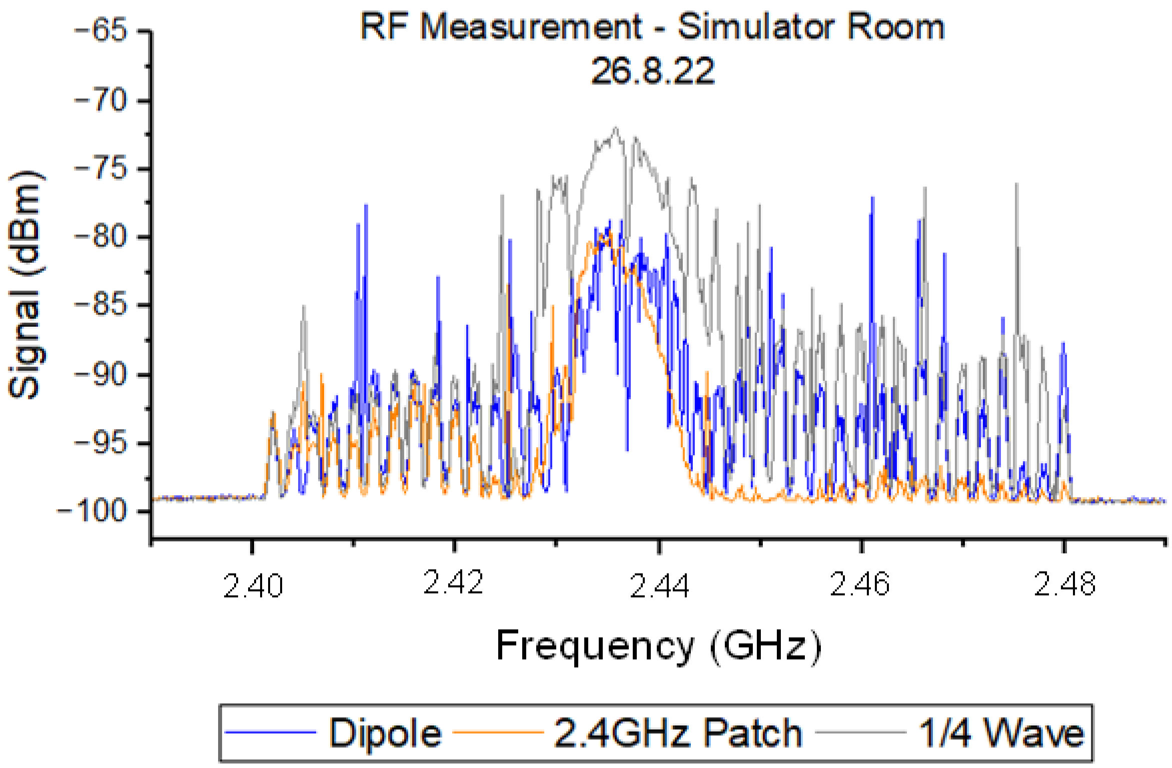

Figure 3.35 - RF measurements – simulator room on 26.08.2022 (dBm)

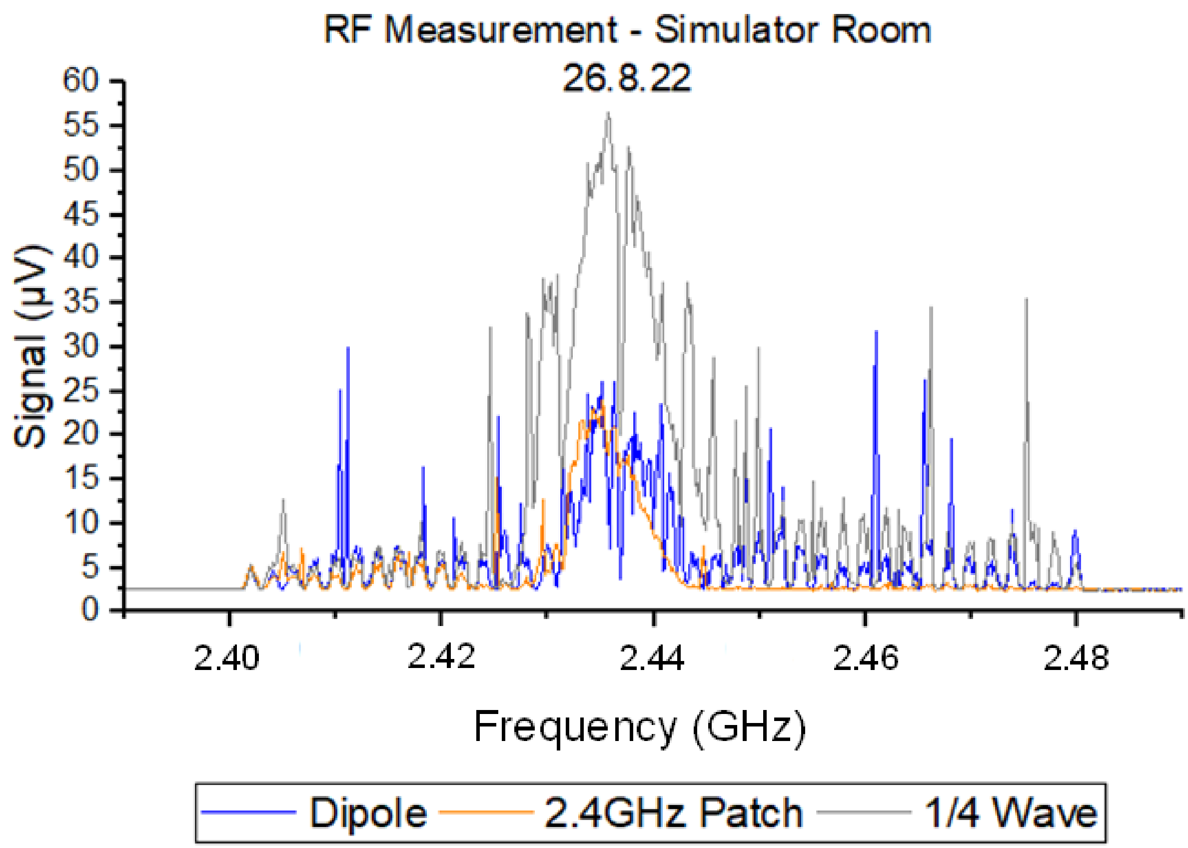

Figure 3.36 - RF measurements – simulator room on 26.08.2022 (microV)

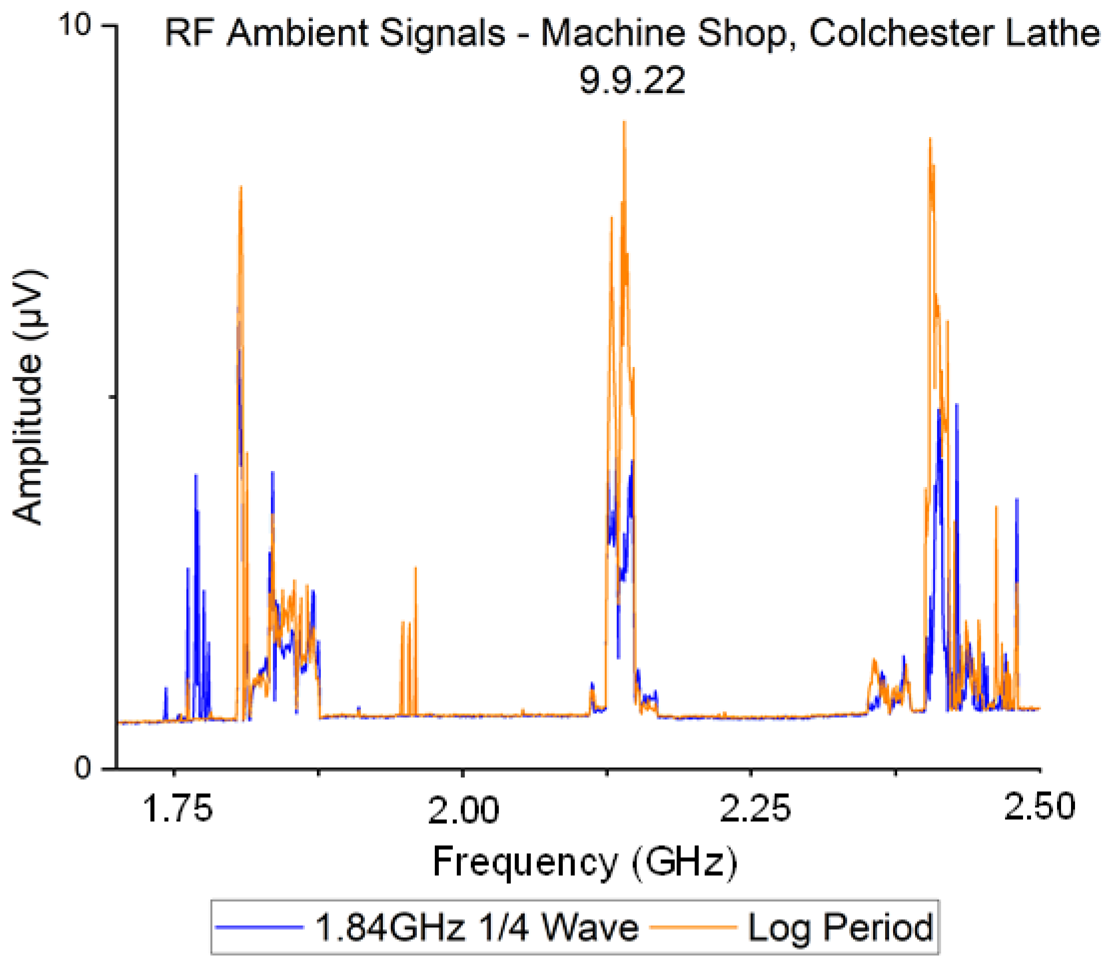

Figure 3.37 - RF ambient signals – machine shop, Colchester lathe on 09.09.2022

As demonstrated by the aforementioned results, at its peak performance, the most responsive antenna (orange trace - the Log Periodic) only succeeds in generating a modest 60 microvolts or less of harvestable energy (Ibrahim et al., 2022; Olgun et al., 2011). Unfortunately, this output is not maintained consistently, thus accentuating a significant limitation with these energy harvesting processes. The following chapter will concentrate on addressing this issue and potential solutions to improve the efficiency of energy harvesting from radio waves (Ibrahim et al., 2022; Olgun et al., 2011).

3.6 Limitations of RF antennas for energy harvesting

Dissipative electrical systems typically have an amount of electrical noise generated (Crescimanno,1993) when in use as a by-product. This phenomenon can be attributed to the finite thermal excitation experienced by the electrons within the system. As a result of this thermal stimulation, the electrons undergo a series of intricate interactions and movements, which ultimately contribute to the observed behaviour. By understanding the underlying processes, it becomes possible to gain a deeper insight into the relationship between thermal excitation and the properties of the system as a whole. The resulting noise is closely related to the blackbody emissions (Ruffio et al., 2018) generated by objects at a predetermined temperature, thermal noise generally exhibits a similar frequency spectrum across various instances. At conventional operating temperatures, the most substantial emission is predominantly concentrated within the mid-infrared range, which considerably surpasses any frequency of potential interest for specific applications. Consequently, when considering microwave purposes, this form of noise can be effectively regarded as frequency-independent.

This understanding of thermal noise and its relationship to frequency allows for a more comprehensive and nuanced approach when dealing with potential interference or signal disruptions in various applications. By acknowledging the frequency-independent nature of thermal noise within the context of microwave systems, it becomes feasible to develop more effective strategies and designs that account for this inherent characteristic.

It is known that for any source resistance R, the maximum noise power is delivered and matched (Massaguer & Massaguer, 2021) to a load of the same resistance, and in this case is independent of the value of the resistance. This resulting noise influences the amount of usable energy that can be harvested. CE markings help identify frequencies to focus on, but result is overall less power available from harvesting than expected.

Ukala et al. (2023) addressed RF losses due to interference from EMI, thus the above results showing very minimal Voltage contribution from the harvesting antenna is not surprising and leads to the further work that is carried out in this thesis to fully integrate the energy obtained through RF harvesting. This work is shown below, as well as subsequent recalculations. The result from the investigation and the full calculations showing that a very negligible amount is actually lost – certainly not significant enough to challenge the viability of RF use where sufficient energy can be captured.

The Trapezoidal method is used to calculate the voltage generated from the graph:

$$\int_a^b f(x)dx \approx \sum_{i=0}^{n-1} h\frac{f(x_i)+f(x_{i+1})}{2} \tag{3.23}$$

3.7 RF Element Summary

The hypothesis of this thesis, revolving around the efficiency and effectiveness of antennas for energy harvesting in batch manufacturing, finds a concrete grounding in the detailed analysis of RF elements presented in the previous sections. Each element has been scrutinised not only for its theoretical significance but also for its practical applicability in the design and operation of antennas. By integrating novel RF energy harvesting techniques into different configurations of antenna design, new avenues in the field of energy-efficient manufacturing can be explored. This integration is a direct response to the challenges and opportunities identified in earlier sections, particularly in sections discussing novel materials for RF TEG designs and the application of RF thermoelectric generators.

The comprehensive analysis of RF energy harvesting elements presented so far is instrumental in validating the hypothesis. The conceptual foundation aligns with the practical aspects discussed in subsequent sections. It clarifies the critical role these elements play in the design and functionality of antennas, and underscores this thesis's contribution to the technological advancement in energy harvesting, reflecting both an academic and practical contribution to the field of antenna design and sustainable manufacturing practices. As highlighted in the 'contribution to knowledge' section, the insights offered here add a new layer to the existing body of knowledge in RF energy harvesting. The practical implications of these elements in batch manufacturing, particularly in their role in promoting low carbon operations and striving towards net zero goals, have been emphasised.

From basic principles, it is known that power is a factor of voltage (V) and current (A).

More specifically it is the product of voltage and current, as per

$$P = VI \tag{3.24}$$

Grasping their interplay is crucial when examining the limitations and efficiency of energy harvesting from radio frequency (RF) sources. Energy harvesting from RF sources presents several challenges, mainly due to the low levels of accessible power, the fluctuating nature of RF sources, and the inefficiencies present in the energy conversion process (Ibrahim et al., 2022). The main challenges associated with this process include the low and fluctuating levels of accessible power and the inherent inefficiencies in the energy conversion process (Ibrahim et al., 2022; Visser & Vullers, 2013). And this has been the same limitation experienced in this study. With the use of a voltage multiplier, the study still found that the nominal current required to operate the device was seldomly met, and even when there was a spike during peak readouts, it was not sustained for long enough to allow reasonably useful power to be harvested. As a result, the following stages of the research will focus on the TEG element and as such, the bulk of the quantitative analysis will be carried out using data obtained from the TEG element.

4. GAINS WITH TEG MODULES

The detailed exploration of literature in the preceding chapters has yielded critical insights and data, which are pivotal to the research presented in this chapter. Specifically, the following key areas have been compiled and analysed from the discussions in Chapters 1, 2, and 3:

- Current practices for reducing greenhouse gas (GHG) emissions in manufacturing, as detailed in Chapter 2, where various strategies and methodologies have been explored.
- The commonly identified barriers to implementing a successful net-zero strategy, discussed in Chapter 2, highlighting the challenges faced by organisations in achieving sustainability goals.
- Solutions to overcome these barriers, as elaborated in Chapters 2 and 3, presenting practical and effective approaches to address the challenges.
- The concept of integrating energy scavenging in manufacturing, as a means to recover any lost energy, discussed in Chapter 1. This section delves into innovative techniques for energy efficiency and recovery.

These elements, drawn from the specific sections of the earlier chapters, have been synthesised into a comprehensive guideline. This synthesis forms the foundation of the proposed solution aimed at achieving net-zero emissions in manufacturing environments. In light of all the considerations and findings presented in the aforementioned chapters, this chapter proposes a novel hybrid Energy Harvesting device. This device is designed to operate efficiently within a batch manufacturing setting, aligning with the strategies, challenges, and solutions identified in the previous sections. The development of this device represents a practical application of the research, contributing to the broader goal of sustainable manufacturing practices.

With all the considerations and findings, a hybrid Energy Harvesting device that works within a batch manufacturing environment is proposed as depicted in Figure 4.1.

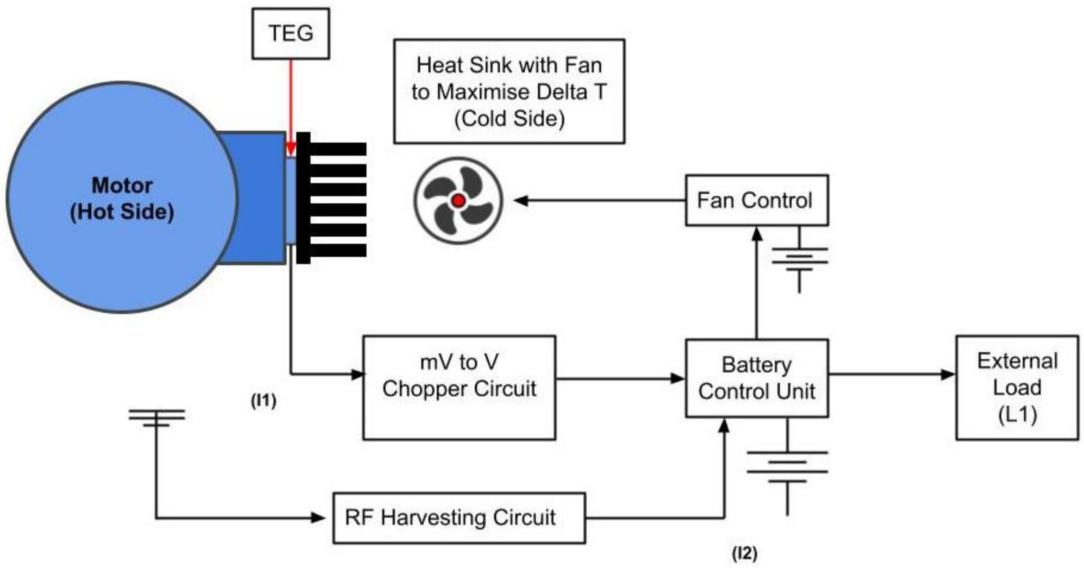

Figure 4.1 – Batch manufacturing energy harvesting device

A depiction of the working schematic is shown above. The waste heat from the motor provides thermal energy to the hot side of the TEG. The heatsink with a fan attached subsequently provides the cold side of the TEG some additional heat extraction by way of mechanical heat extraction/cooling to further improve ambient temperature thus maximising the temperature differential (ΔT) for the TEG.

The TEG generates a small voltage by means of the Seebeck effect from the temperature difference between the hot side and the cold side of the TEG thus creating energy **I1**.

A “boost” switch mode chopper circuit converts the low voltage from the TEG to a higher voltage (at lower current) to allow the battery to be charged. A similar voltage multiplier is also implemented to harvested RF energy thus also generating some voltage **I2.** Note that a small amount of power is required to run the clock of the chopper circuit, which can be drawn from the battery. The circuit will not operate unless this clock is present.

When sufficient charge has been accumulated in the battery, then the Battery control circuit provides power to the external load. If there is sufficient waste heat, then the external load is powered continuously depicted in **L1**.

Where there is a large enough “hot” surface, then more TEG elements can be arranged around the periphery. Electrically, these can either be in series or in a series-parallel configuration to allow the available power to be matched to the load presented by the chopper circuit.

The initial scope of the work was based around utilising the Voltage obtained from RF antenna to be multiplied using a Mosfet setup in order to drive the cooling fan attached to the fin of the cold side of the TEG saddle, thus driving the temperature down and creating a greater temperature gradient to generate more energy from the TEG setup. After the findings from initial test runs and calculations showing that not enough amps were being produced from the RF setup to produce reasonable sustained power from RF alone, the decision is made to utilise the voltage multiplier across the board.

Figure 4.2 shows the circuit diagram for the TEG Converter.

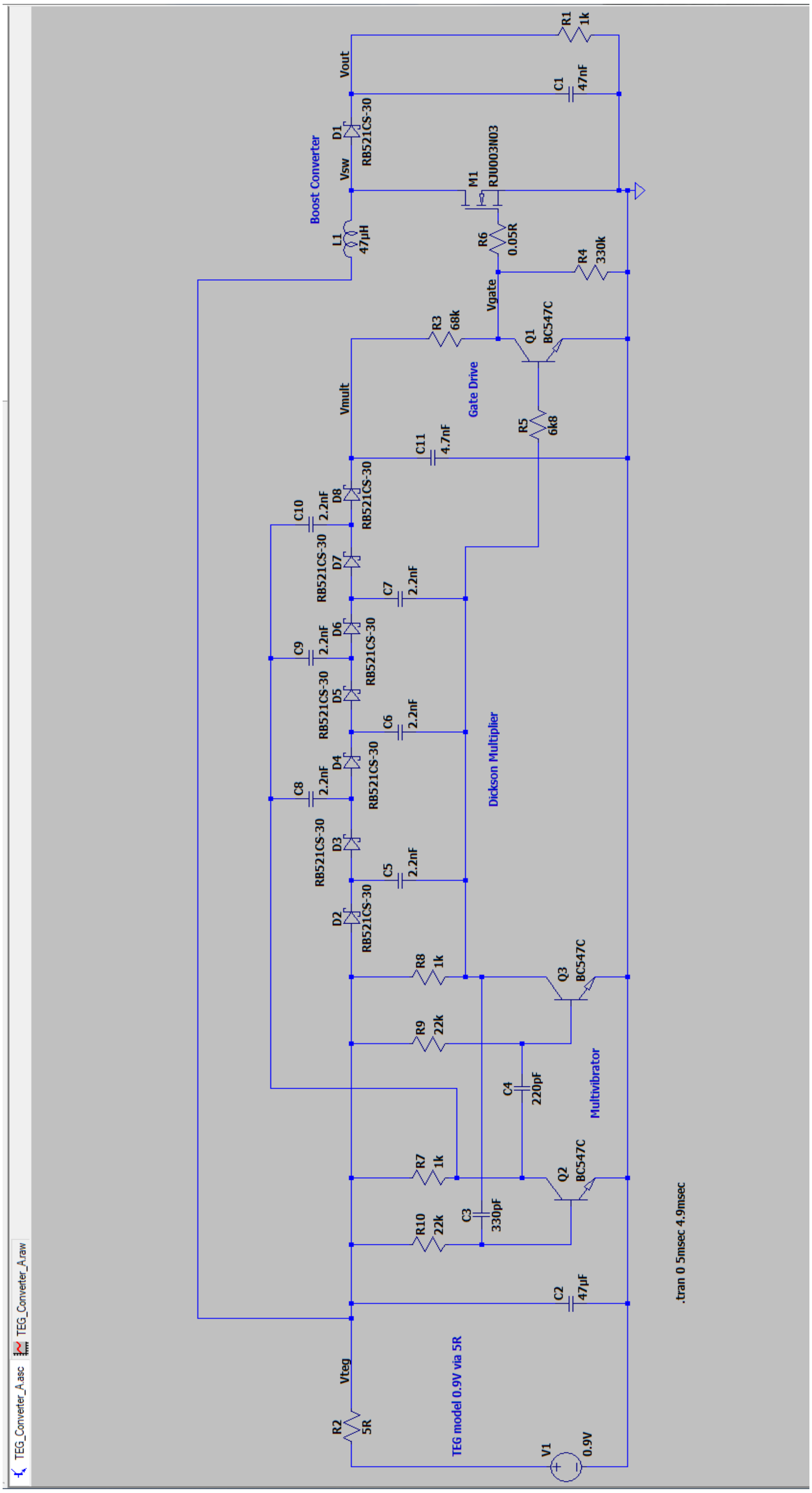

Figure 4.2 – Circuit diagram of TEG converter from the LTSPICE model

System outline:

TEG model

- Multivibrator circuit to provide the clock for both the boost converter and the Dickson.
- Dickson multiplier to create enough voltage to drive the gate of the Mosfet in the Boost converter.
- Gate drive circuit to drive the gate of the Mosfet.
- Boost converter to convert 900mV to 4V (or more) in order to charge a LiPo battery (or similar load).
- 1k load resistor (actual load tried was 4k7)

The starting point of the design is the known output characteristics of the TEG assembly when mounted on the AC motor with the fan and heatsink for the cold side of the TEG. The two TEGs are able to generate 900mV with a series resistance of 4.2 ohms for a 10 deg C temperature difference (hot side at 50 deg C).

The open loop boost converter (formed from L1, M1, D1 and C1 in the model above) can generate sufficient voltage to charge a single LiPo battery (3.2V to 4.2V) from 900mV provided that there is a clock signal, the duty cycle is sufficient and that there is enough voltage available to drive the gate of the Mosfet. The relationship between the input and output voltages for this system requires an ideal duty cycle of 82%. A duty cycle on either side of this value results in poorer efficiency and a lower output voltage (effectively a lower output power, necessitating a higher load resistance).

The need for a clock signal requires a circuit form that can operate from 900mV and deliver a suitable duty cycle. The classic “multivibrator” circuit is useful in that with suitable choices of resistor, the circuit can operate from lower than 900mV (provided some variation of frequency is accepted). In this system the multivibrator is formed from the circuit around Q2 and Q3. The resistor values are chosen to operate at low currents to assist the overall efficiency. The transistors are able to provide a collector voltage swing of 700mV at around 0.7mA collector current at a frequency near 100kHz.

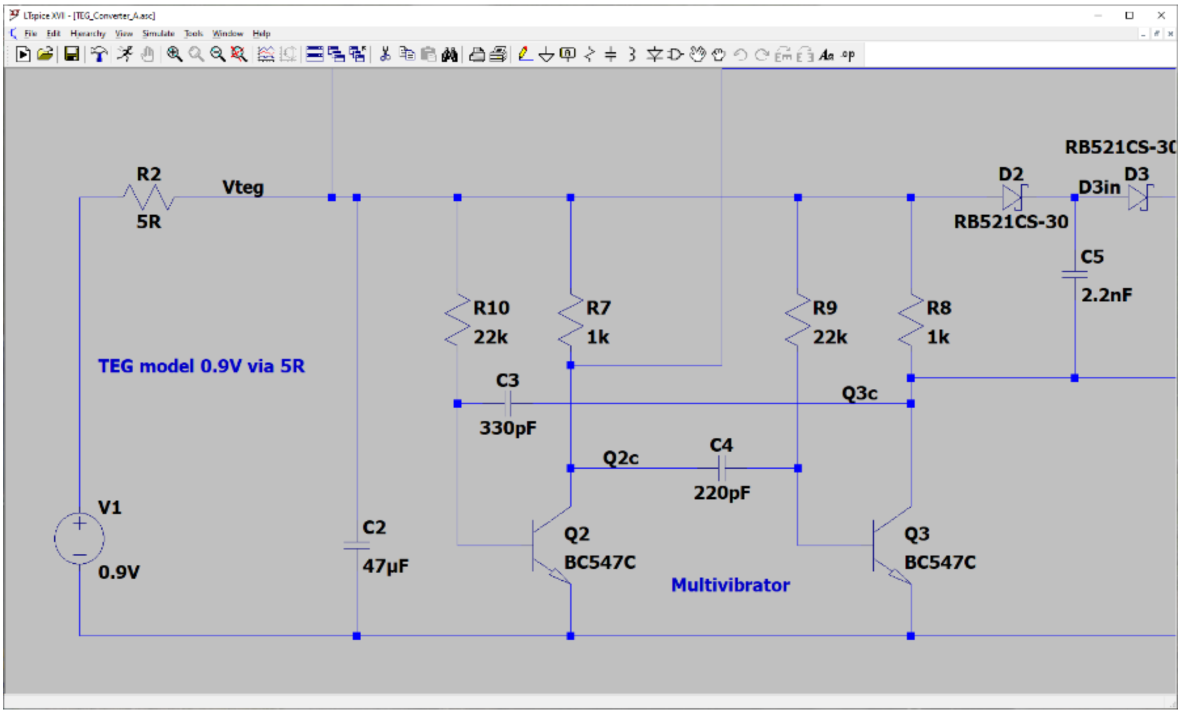

Figure 4.3 – Detailed multivibrator

The duty cycle is asymmetric, set by the values of C3 and C4 to approach the duty cycle required by the Boost convertor.

The period is set by the sum of the two-time constants (R10*C3) and (R9*C4). The base voltage is an exponential rising signal Vbase = A.Exp (-t/torr) where torr = R9*C4, t = time, A = supply voltage 900mV. When Vbase exceeds 0.6V then the silicon NPN transistor (Q2 or Q3) begins to turn on and the collector current rises, creating the next transition on the output. The varying input characteristics of the base-emitter circuit do modify the simple exponential rise equation, where a full non-linear circuit model is more accurate.

Initial observations were that the multivibrator operating at a low voltage and collector current does not provide a fast risetime. Earlier prototype using a lower collector current and subsequently the design is evolved after the Dickson is added to the system.

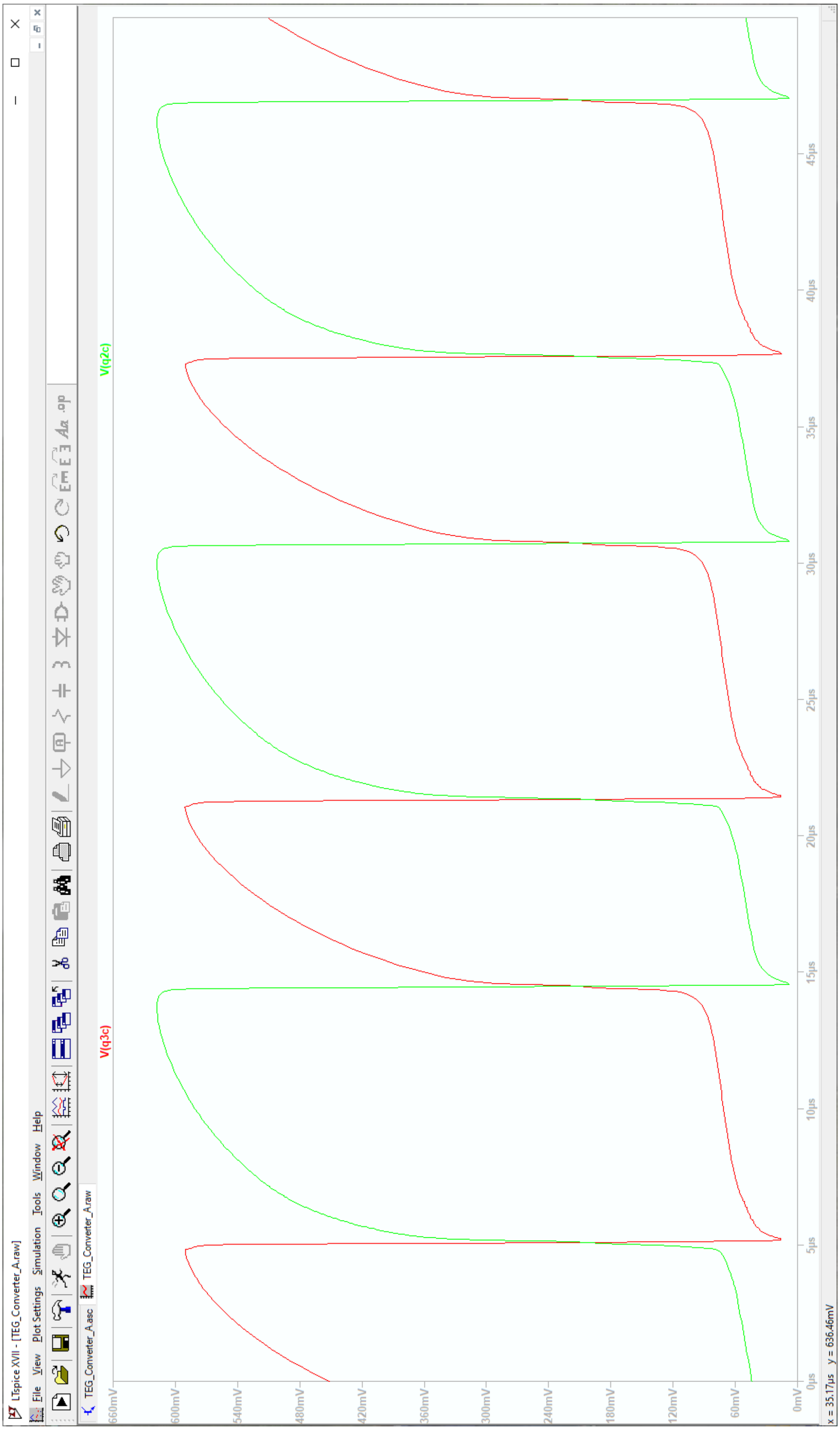

Figure 4.4 - Collector waveforms for multivibrator

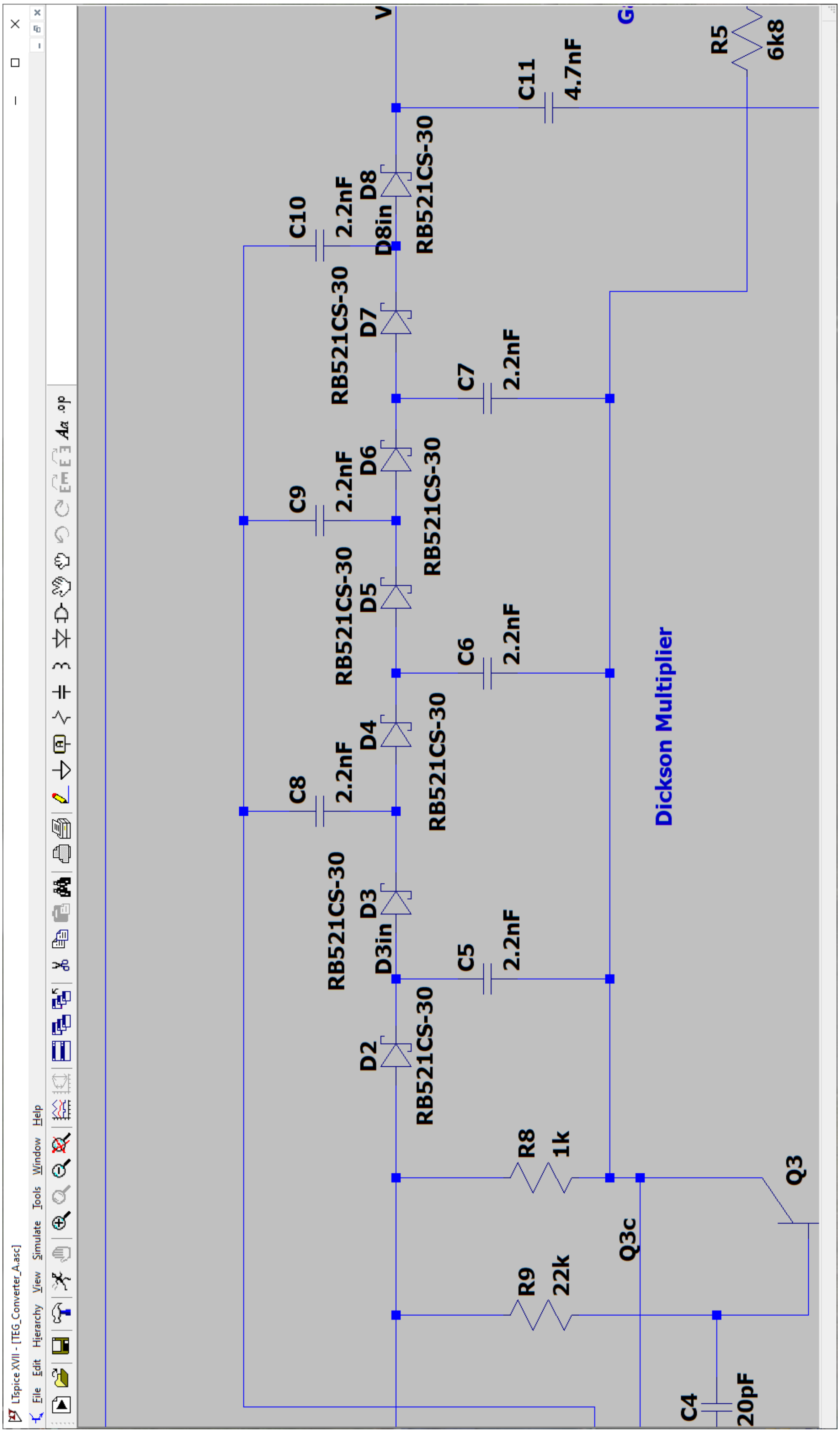

Figure 4.5 - Dickson multiplier

The gate voltage required to allow the Mosfet (M1) to reach a low drain-source resistance is in the region of 1.7V to 2.5V (depending on the particular device in the built converter). The voltage from the TEG alone is still too low. The output from the multivibrator is even lower. This leads to the need for some form of voltage multiplier. Given that the multivibrator provides two outputs, at 180 degrees relative phase, the Dickson form is useful as it requires two clocks with this phase relationship. In this circuit, the Dickson is made up of D2 to D8, with C5 to C10 providing the capacitive coupling to the clock signals. A model was tried that only had D2 to D6, but this did not provide enough output voltage, so adding the extra stage of D7 and D8. This provided enough voltage for the Gate Drive circuit to switch the Mosfet. The forward voltage drop of the Schottky diodes (D2-D8) is large at (200mV to 300mV) relative to the available TEG voltage (900mV) which makes the circuit far less effective and thus requiring more stages.

It is noted that a limitation of the Dickson form is that it ideally requires a 50% duty cycle clock signal, which conflicts with the needs of the Boost converter in this case. The Dickson form also transfers most of the current from the capacitors after the leading edge of the clock, suggesting that a fast rise-time is preferred.

The basic Gate Drive circuit is simply to couple the clock signal from the Multivibrator to the gate of the Mosfet, the upper drive voltage being provided from the output of the Dickson multiplier. The circuit utilises an NPN transistor in a common emitter configuration to provide the gate signal.

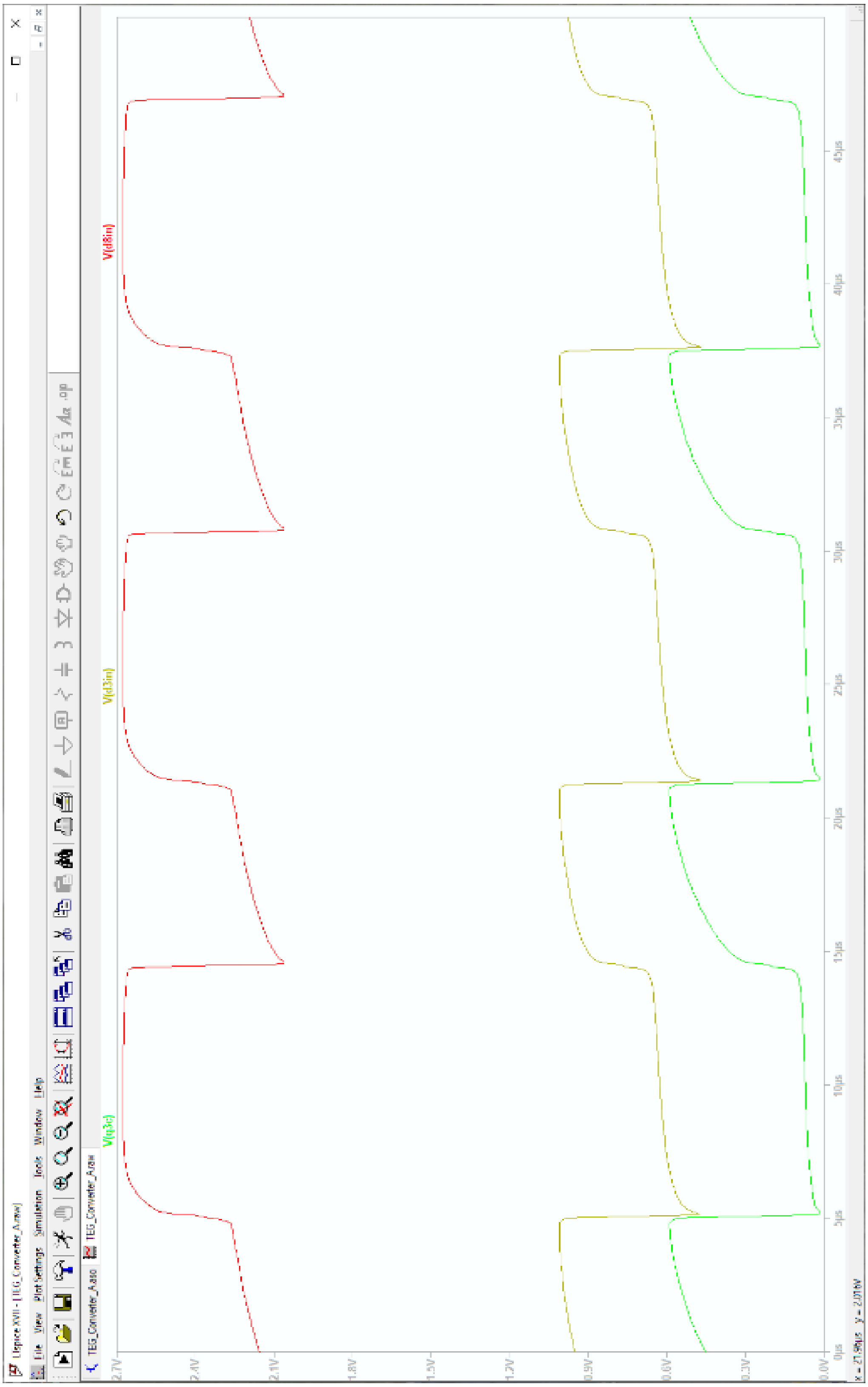

Figure 4.6 - Dickinson multiplier waveforms; Q3 collector (Green), signal at D3 anode (Straw) and the signal at D8 anode (Red) showing the increasing voltage after each stage

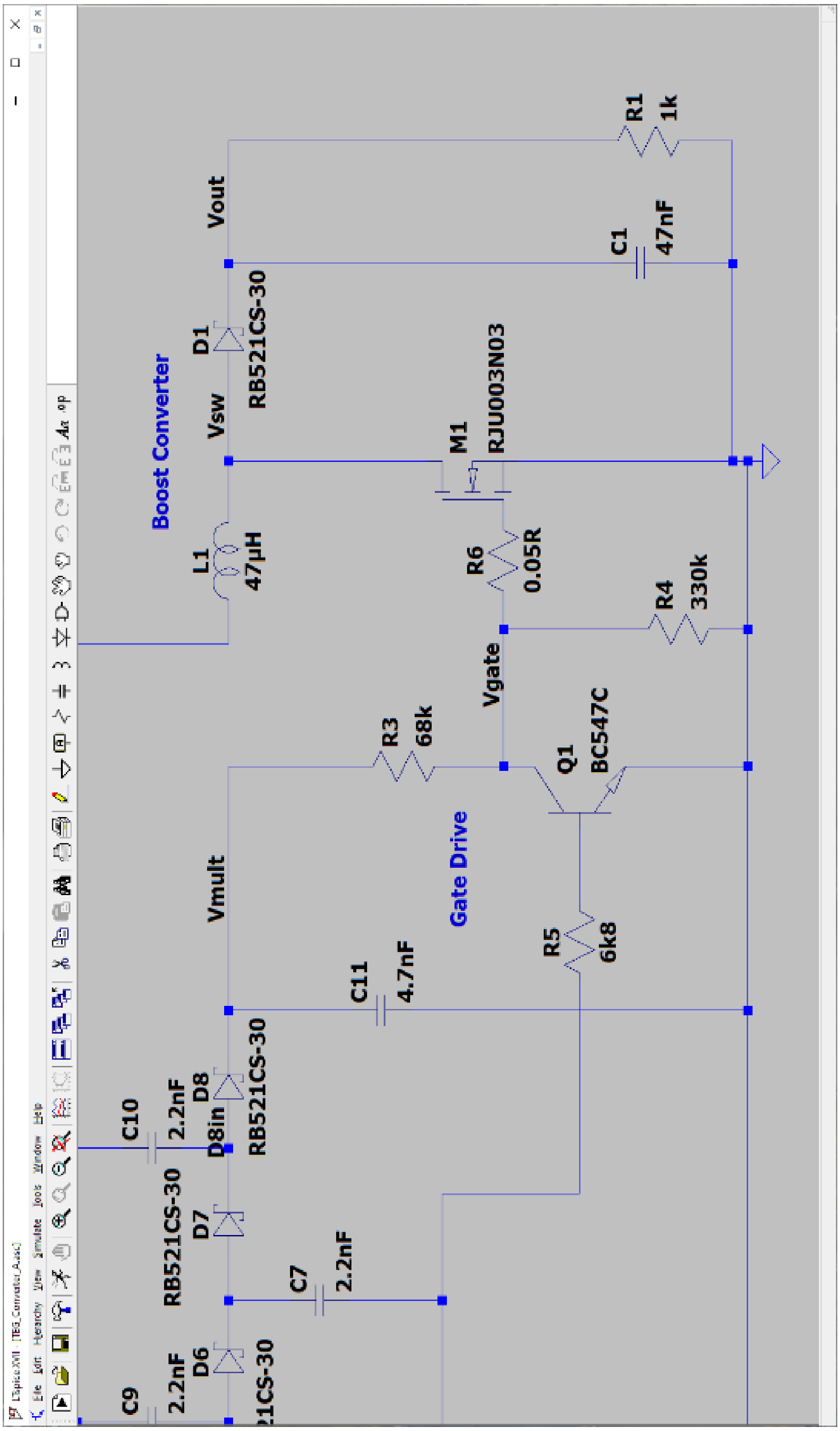

Figure 4.7 - Dickson multiplier chain

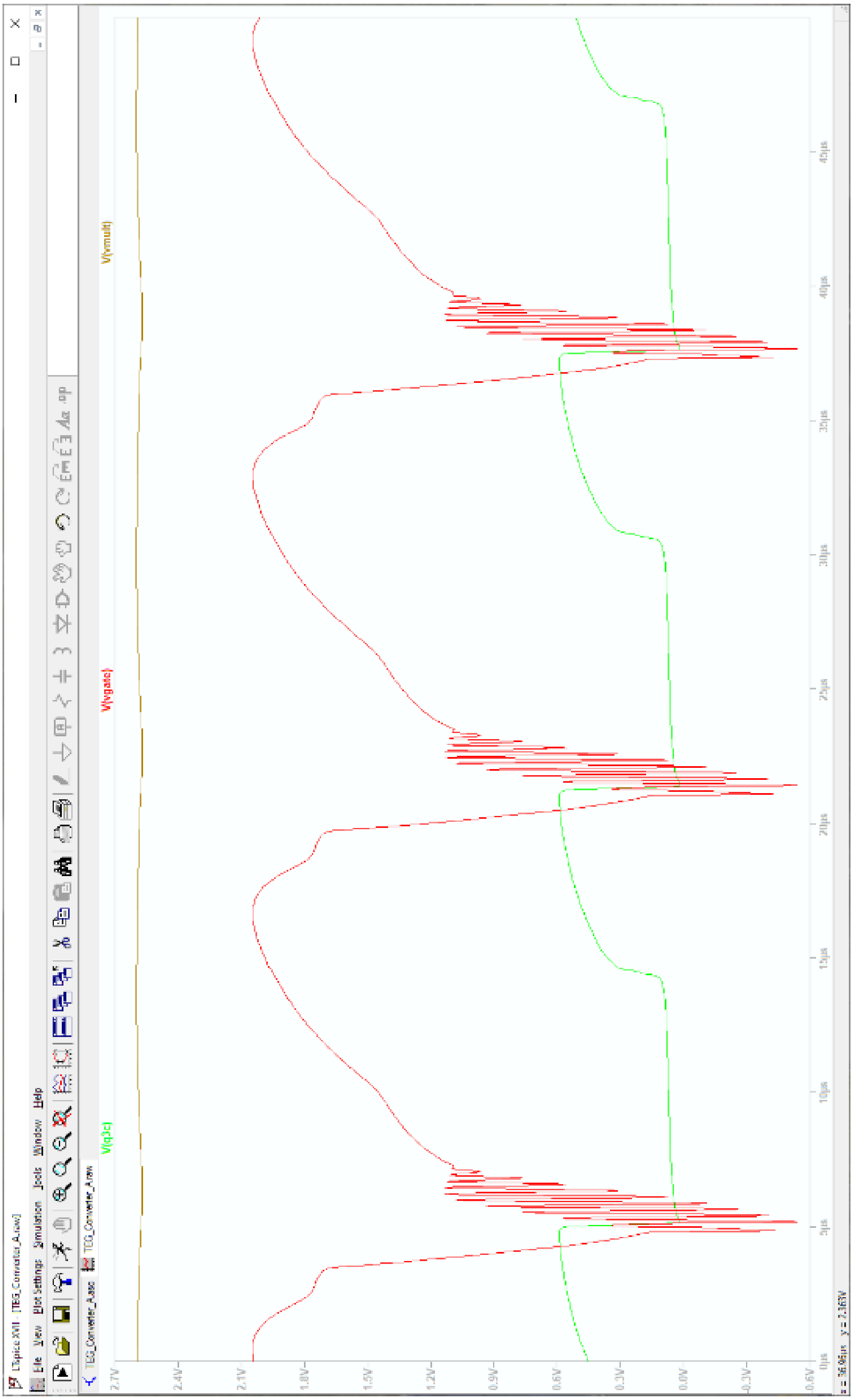

Figure 4.8 - “Vmult” (Straw) and the gate voltage “Vgate” (Red) for Dickinson multiplier chain

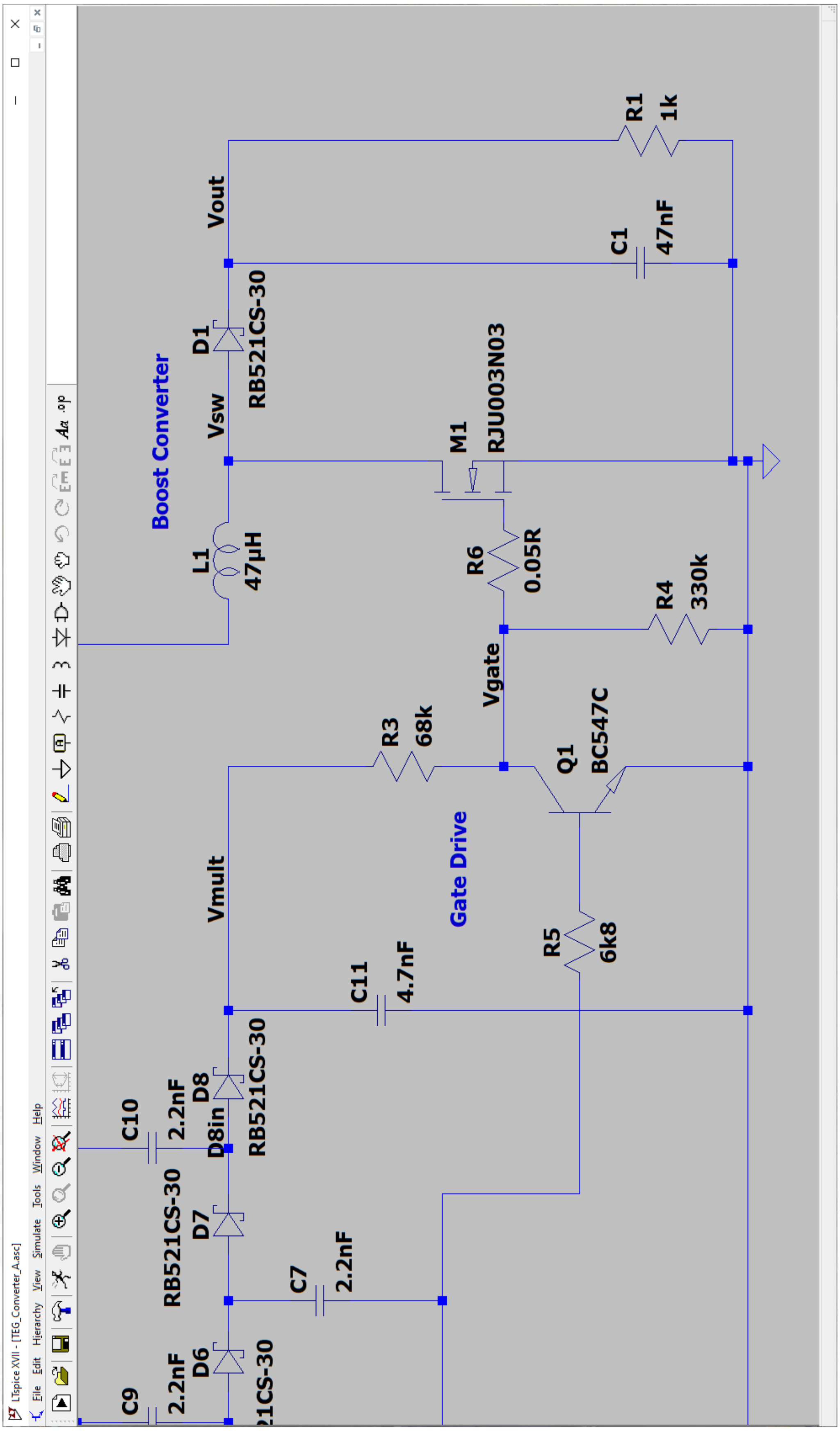

Figure 4.9 - Gate drive and Boost converter

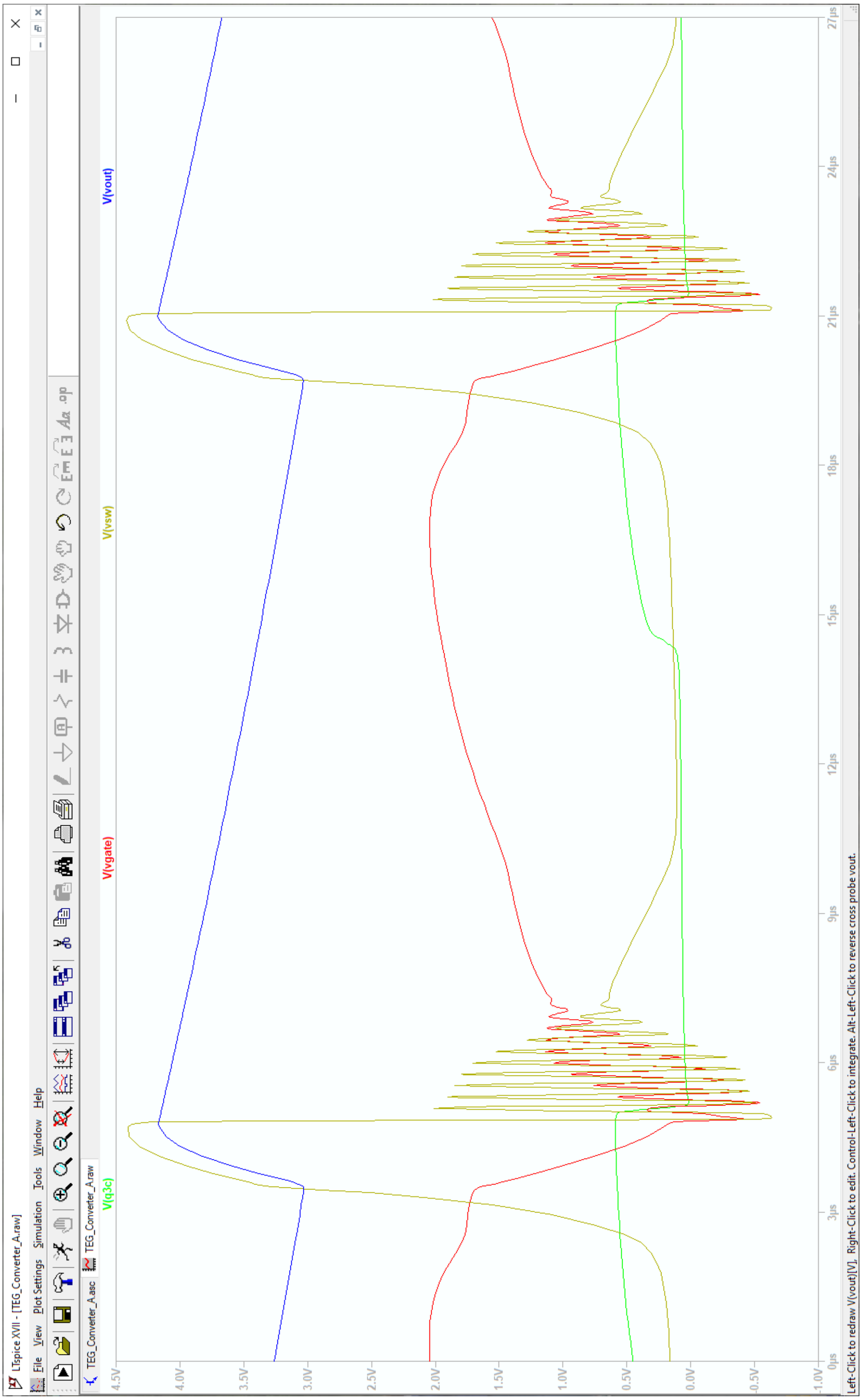

Figure 4.10 - Gate drive and Boost converter waveforms. The output voltage is “Vout “(pale Blue), the switch node is “Vsw” (Straw)

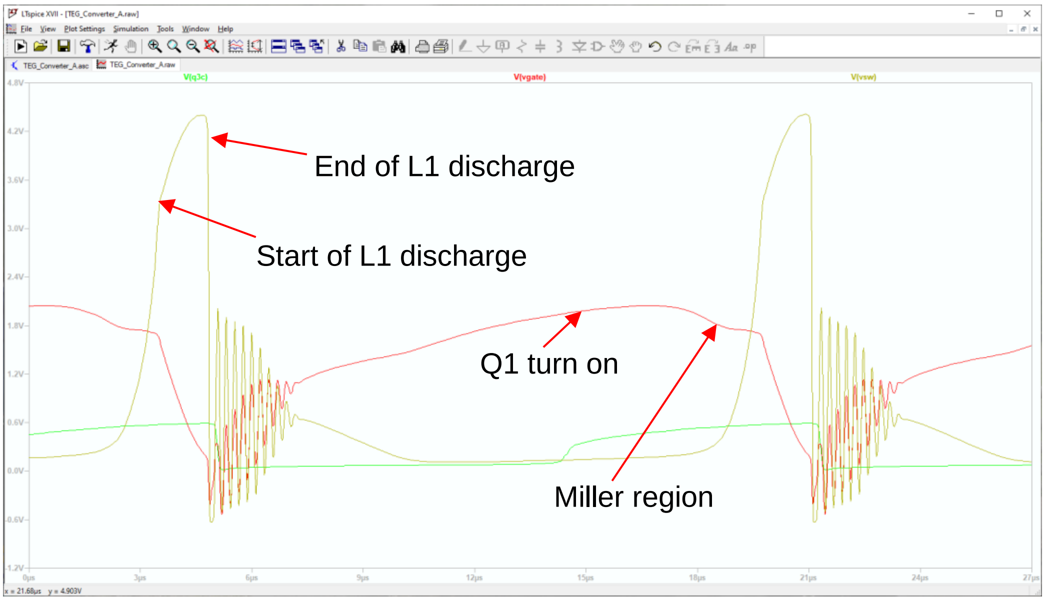

Figure 4.11 - Detailed analysis of the Switch node (VSW, Straw), the gate voltage (Vgate, Red) and the gate clock (q3c Green).

The main sequence of events as depicted in Figure 4.11 are described below:

1. Start of L1 discharge via the Schottky diode (D1).
2. End of L1 discharge as the Schottky diode switches off.
3. Ringing after the Schottky diode switches off.
4. Slow rise of the gate voltage via R3 until M1 channel conducts and damps the ringing.
5. Gate clock signal rises, turning Q1 on.
6. Gate voltage discharges into Q1 collector relatively slowly until the rising Drain voltage results in the Miller plateau, coupled via the Drain-gate capacitance in M1.
7. M1 gate is then on until the end of the Miller region when the gate voltage falls rapidly.
8. M1 then turns off. This allows the inductor L1 to begin the discharge and the cycle repeats.

The net effect of this slow gate 'turn on' – 'turn off' signals is to alter the duty cycle so that the 58% duty cycle of the multivibrator is extended to 77%. This is nearer to the ideal 82% for a boost converter working between 0.9V input and 5V output. This setup presents the final working model and is tested on an oscilloscope for verification.

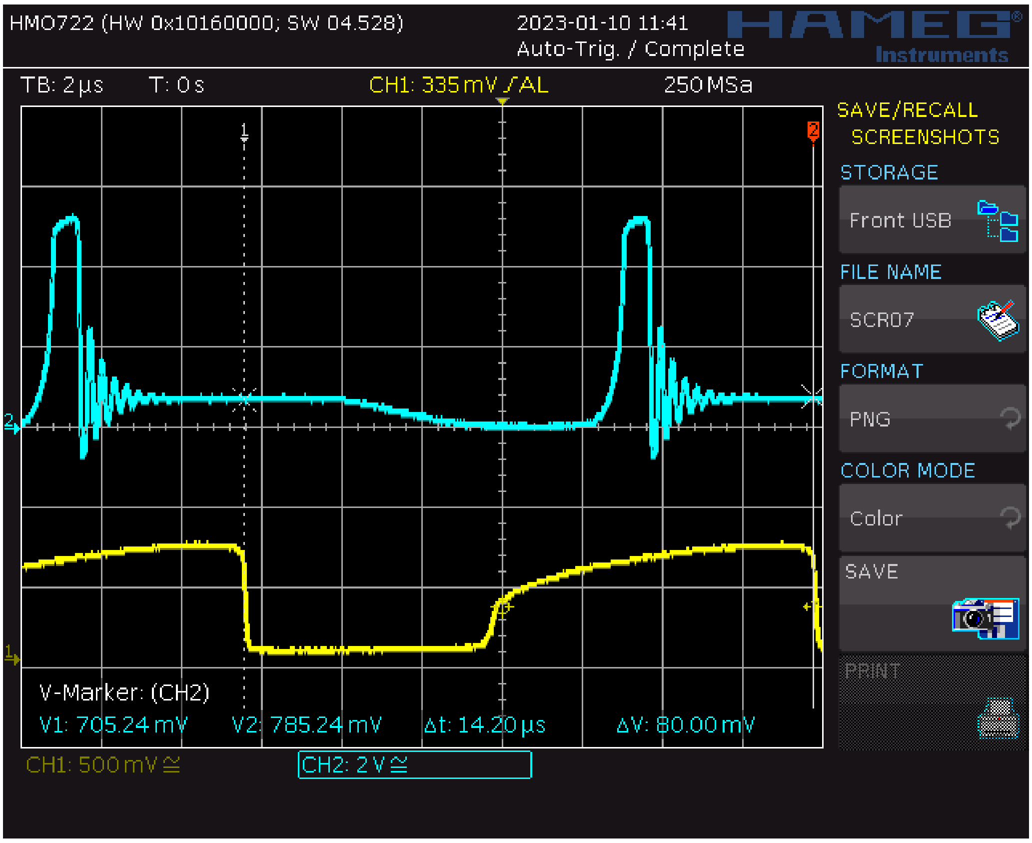

Figure 4.12 - Oscilloscope readout showing the clock to the Gate Drive (Ch1 Yellow) and the Switch node (Ch2 Blue).

For testing, the input voltage was 0.9V via a 4R7 resistor to mimic the TEG source voltage and impedance.

The signals show that the circuit response differs from the model in several ways. The multivibrator is running faster at 14.2usec period (compared to model 16.18usec).

The period where the gate drive to M1 is clearly shorter at around 3.36usec (model 7.4usec). This difference is probably due to the gate capacitance and gate charge characteristics of the particular mosfet fitted to the board. Also, as the stray capacitance from the layout on Veroboard was not modelled it is expected that this will slow the charging period of the gate.

The duration of the conduction period of the Schottky diode is shorter at 0.8usec (model 1.27usec).

When the circuit was built, the combination of the Dickson multiplier and the particular Mosfet worked very well, sufficient gate voltage was observed. The overall result was that a useful output voltage was obtained into a 4k7 load resistance.

To conclude, these are promising results and will be built upon and implemented to a multiple stack of the built RF-TEG harvester and tested to observe the gross energy that is harvested after taking into account any losses. The hope is to observe a clear pattern thus allowing an accurate extrapolation for a scaled version of such device.

4.1.1 Optimising the gains from TEG

As previous chapters have covered, TEG's generate electricity as a result of a difference in temperature, thus given that the intention is to maximise the efficiency in generating electricity, it is important that an effort is made to stabilise said temperature difference. For this study, the use of a heatsink has been implemented with further use of cooling fans put in place to maintain/maximise the temperature difference from the hot and cold side. The placement of the cooling fan has been dictated through the use of thermal loading analysis. This section of this thesis explores this.

Thermal loading test is a critical aspect of understanding the performance and functionality of a heat sink under various temperature conditions. In this test, the base temperature of the environment is set to 15 degrees Celsius. The heat sink is clamped down on its bottom surface, replicating the natural loading conditions it would experience in actual use (Zahid et al., 2022). To better understand the performance of the heat sink, the loading temperature is increased to its working temperature of 60 degrees Celsius (Yang et al, 2021) on a simulation software (CATIA).

As the loading case begins with the heat sink at 15 degrees Celsius, the translational displacement of the component is examined. This refers to the movement of the heat sink as it responds to the temperature change (Yazici et al., 2023). The image provided for this loading case highlights the maximum displacement of 0.0759mm, which occurs at the farthest points of the heat sink (Seetharamu et al., 2019). This information is essential for determining the heat sink's ability to withstand varying temperatures and how it may affect its performance in dissipating heat.

One of the critical factors influencing the performance of a heat sink is the thermal expansion experienced by the material (Khattak and Ali, 2019). When subjected to temperature changes, materials tend to expand or contract, which can result in stress and deformation within the component. The translational displacement observed in the loading test is a direct result of this thermal expansion ((Mohammadipour and Willam, 2017). It is crucial to consider the magnitude of this displacement in the design and selection of a heat sink to ensure that it maintains its structural integrity and performance under the desired operating conditions.

The test under consideration reveals that the heat sink experiences a maximum displacement of 0.0759mm at its extremities when subjected to a temperature change from 15 degrees Celsius to 60 degrees Celsius. This data is valuable for engineers and designers who need to account for the impact of temperature changes on the heat sink's performance (He, Yan and Zhang, 2021). For example, if the heat sink is used in a system with sensitive components that cannot tolerate significant displacement, the designers may need to reconsider their choice of material or explore other heat sink designs to minimise the impact of thermal expansion (Huang et al., 2023) – in practical terms, this is a validation test to show that the heatsink will dissipate heat efficiently enough for the application (up to 60 degrees Celsius).

Furthermore, understanding the translational displacement of the heat sink allows engineers to predict potential failure points or areas where the heat sink may become less effective in dissipating heat due to deformation (Mohammadipour and Willam, 2017). By identifying these areas, engineers can improve the heat sink design or select alternative materials that exhibit better thermal expansion characteristics (Dhaiban and

Hussein, 2020).

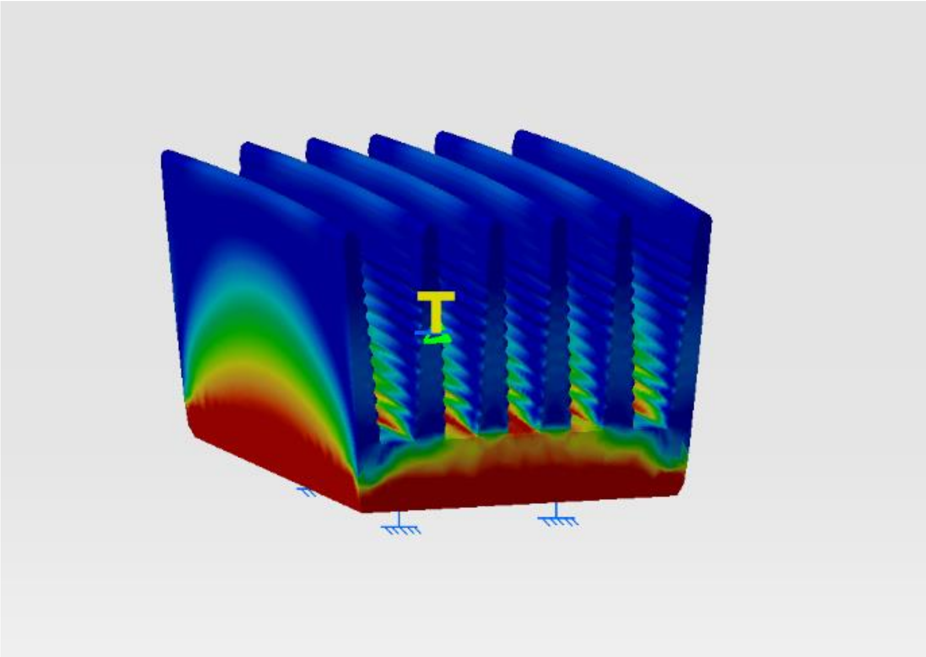

Figure 4.13 - Thermal Modelling results for the heatsink, showing thermal Von Mises stress contours

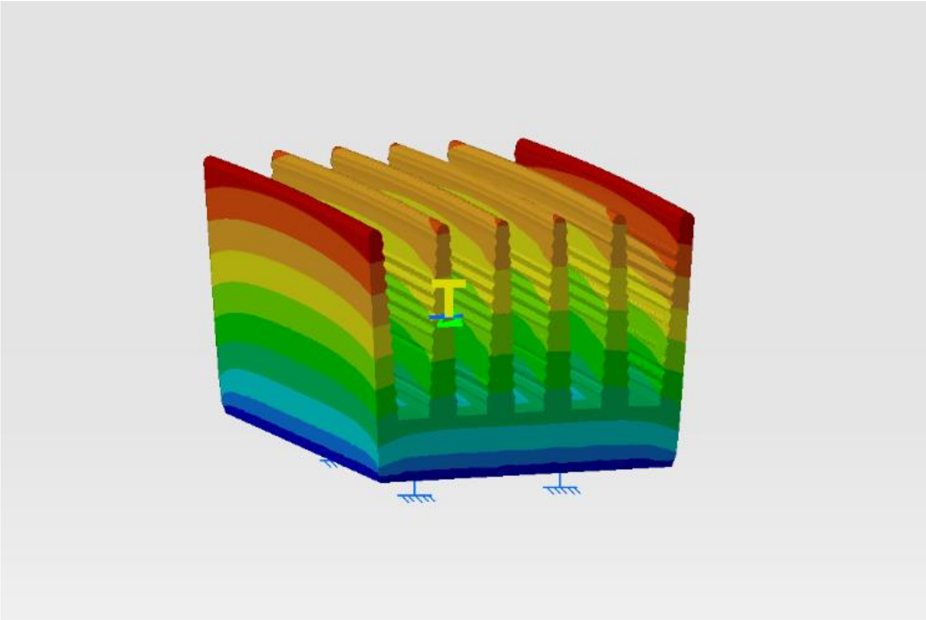

Figure 4.14 - Thermal Modelling results for the heatsink, showing translational displacement contours

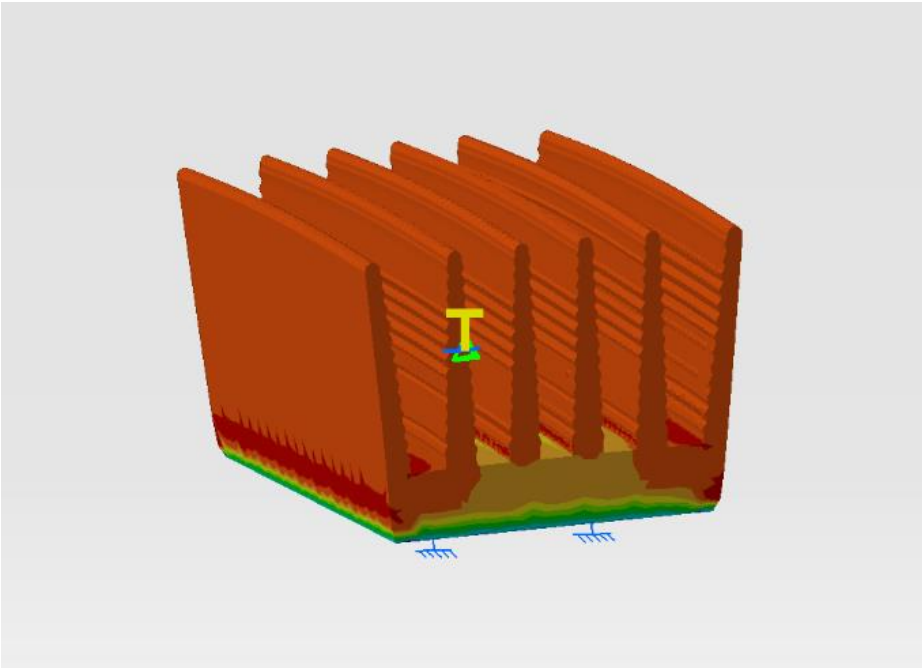

Figure 4.15 - Thermal Modelling results for the heatsink, showing Stress Full Tensor contours.

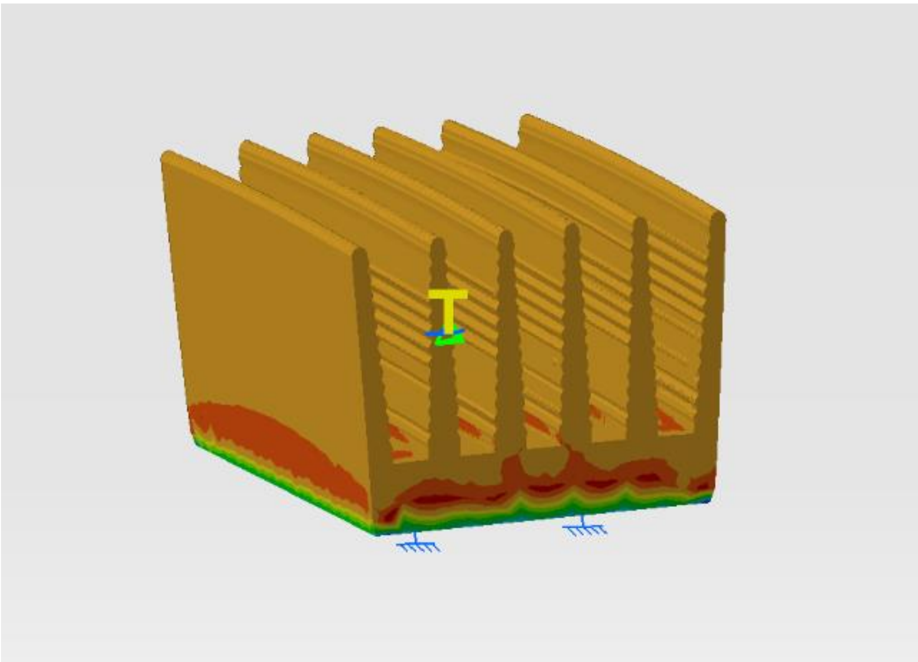

Figure 4.16 - Thermal Modelling results for the heatsink, showing Stress Principal Tensor contours.

The understanding of thermal and mechanical stresses is critical for optimising design for efficiency and longevity. Figure 4.13 represents the distribution of thermal stress within the heatsink material under operating conditions. Von Mises stress is a criterion for determining the yield of materials under complex loading from multiple directions. For heat harvesting, it's essential to ensure that the materials chosen for the heatsink do not reach a stress level that exceeds their yield point, as this could lead to permanent deformation or failure. This figure helps in selecting materials and designs that are robust enough to handle the thermal stresses involved.

Figure 4.14 shows how different parts of the heatsink expand or shift when subjected to heat. In practical applications, thermal expansion can lead to mechanical stress and potential structural failure if not accounted for. Minimising displacement through careful design ensures that the heatsink maintains good thermal contact with both the motor and the TEG, which is crucial for efficient heat transfer.

Figure 4.15 provides a complete picture of the stress state within the heatsink, including both the normal and shear stress components. Full tensor analysis helps in fully characterising the material's behaviour under thermal loads, allowing for the identification of potential failure modes. It also aids in understanding how the heatsink can be optimised to reduce stress concentrations, which can improve the longevity and performance of the heat harvesting system.

Figure 4.16 highlights the maximum normal stress at different points within the heatsink. This figure is critical for identifying any potential weak points in the design that might fail under repeated thermal cycling. Ensuring the principal stresses remain below the material's limits is necessary for a durable and reliable heatsink design in a heat harvesting application.

Additional analysis and considerations can also be made using the heatsink model. For example, thermal gradient visualisation displays the heat sink with a clear thermal gradient indicated by the colour change from red to blue. Red represents the areas with the highest temperatures, and blue represents cooler areas. The gradient is particularly steep near the base, which is where the heat sink contacts the hot side. This visualisation is essential for understanding how efficiently the heat is being conducted away from the motor and across the heat sink, which affects the performance of the TEG device sandwiched in between.

Isothermal contours represent areas of equal temperature and are useful for identifying regions of similar thermal energy. The effectiveness of the heat sink in creating a uniform temperature distribution can be gauged here. Uniform temperature distribution is beneficial for the consistent performance of the TEG device across its entire surface.

In detailed design of the heatsink fins, the colour indicates that there's a gradient along the fins, suggesting that heat is being dissipated along their length. The efficiency of fin design directly affects the surface area available for heat exchange and subsequently the amount of heat that can be harvested. Optimising fin design is crucial for maximising the TEG device's performance.

Finally, while a solid model of the heatsink without the thermal gradient overlay doesn't offer direct insight into thermal performance, understanding the physical structure is necessary when considering manufacturing constraints and how the heat sink and TEG will be integrated with the motor.

Each of these figures plays a vital role in the design and analysis process for a heatsink in a heat harvesting system. They provide insights into the thermal and mechanical challenges that must be overcome to create a system that not only contributes to net-zero manufacturing by recovering waste heat but also operates safely and effectively over the long term. By understanding and addressing the issues highlighted by these figures, engineers can design heatsinks that are better suited for the demanding environment of industrial manufacturing, leading to more sustainable energy use and lower greenhouse gas emissions.

In consideration towards the research topic, each image provides valuable information on the effectiveness of heat distribution and thermal gradient, which affects the TEG's voltage generation capabilities. The uniformity of temperatures across the heat sink for consistent TEG performance is essential, and this simulation shows that the chosen to heatsink will perform optimally.

The detailed structure of the heat sink fins, which are essential for heat dissipation and thus the energy harvesting process is important when selecting the heatsink also to ensure maximum efficiency in dissipating the generated heat. Without knowledge of this, it would be difficult to achieve efficient generation of energy using the TEG. All these tests are carried out using the actual physical model for assessing manufacturability, integration, and the economic viability of the heat sink design towards the TEG consideration.

Assessing the effectiveness of these heat sink designs is crucial in determining how much waste heat can be converted to electricity, potentially reducing the energy consumption of the manufacturing process by reusing waste energy that would otherwise dissipate into the environment.

In conclusion, the loading test of the heat sink at 15 degrees Celsius provides essential information regarding its translational displacement as the temperature increases to its working temperature of 60 degrees Celsius. The observed maximum displacement of 0.0759mm at the extremes of the heat sink is a vital consideration for engineers and designers seeking to optimise the heat sink's performance and ensure its reliability under varying temperature conditions.

This has meant that the extraction fan is placed on the side facing away from the spinning shaft to allow for maximum cooling effect whilst allowing the hot side to be mostly unaffected.

In Figure 4.17, (TEGs) "C" and "B" can be observed, with arrows indicating the position of the saddle component. The saddle, which is composed of aluminium, is situated below the TEG, followed by the fan and heat sink components located at the topmost section of the assembly. To ensure a surface with consistent emissivity for accurate temperature comparison between the saddles, a layer of 3M "Linerless Rubber Splicing Tape" is meticulously applied to the terminal end of each aluminium saddle (3M, n.d.).

This is a necessary step as the aluminium surface exhibits high reflectivity, resulting in low emissivity and thereby causing the thermal camera to register lower-than-actual temperatures (Incropera et al., 2006).

Similarly, Figure 4.18 displays TEGs "OLD" and "A" showcases the saddle positions with arrows, followed by the placement of the TEGs and subsequently, the fan and heat sink components on top. To maintain consistency and facilitate accurate temperature measurements, a strip of 3M "Linerless Rubber Splicing Tape" was also applied to the terminal ends of each aluminium saddle in this setup. This tape application ensures that temperature comparisons can be made reliably, despite the inherent low emissivity of the aluminium surface.

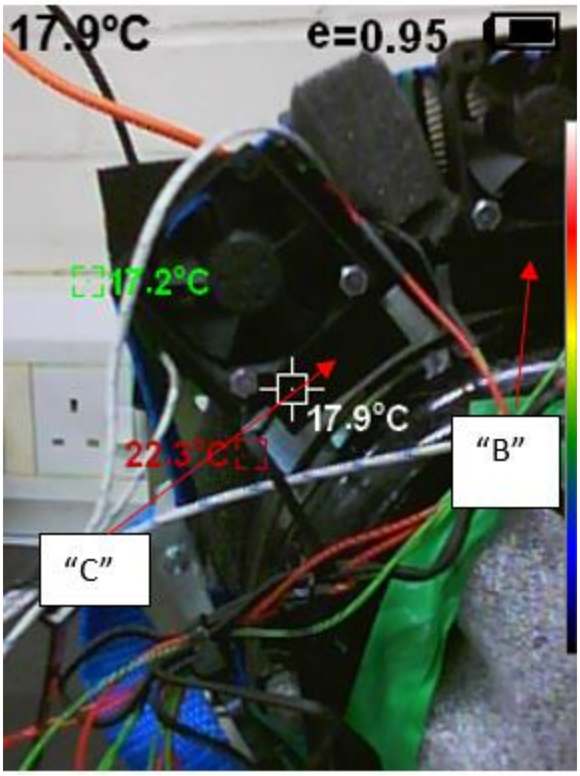

Figure 4.17 - Heatsink testing (observed values)

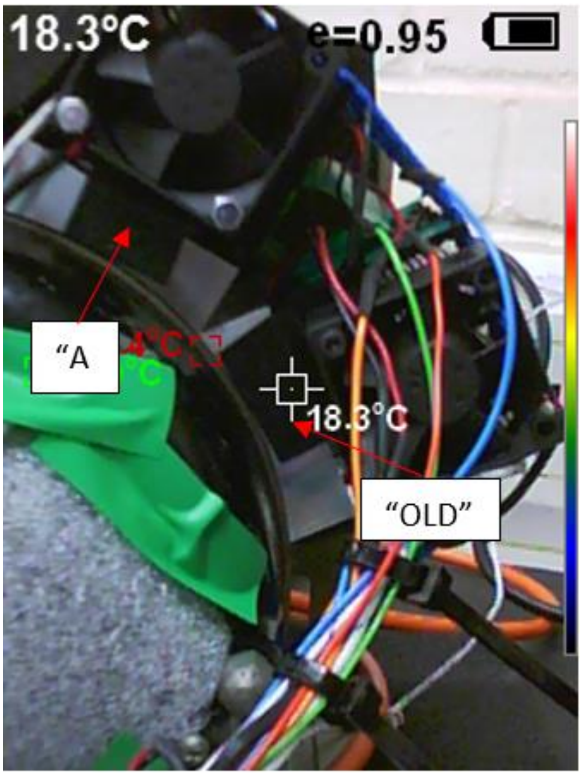

Figure 4.18 - Visible Image showing TEG “OLD” and “A”

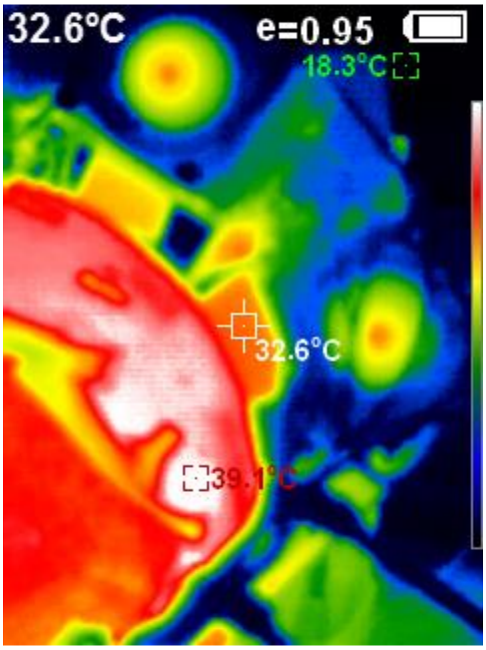

Figure 4.19 - Thermal image of the “OLD” saddle, indicating 32.6C

In Figure 4.18, arrows show the saddle position, TEG above, then the fan and heat sink on top. A piece of 3M “Linerless Rubber Splicing Tape” was applied to the end of each Aluminium saddle to provide a surface with consistent emissivity.

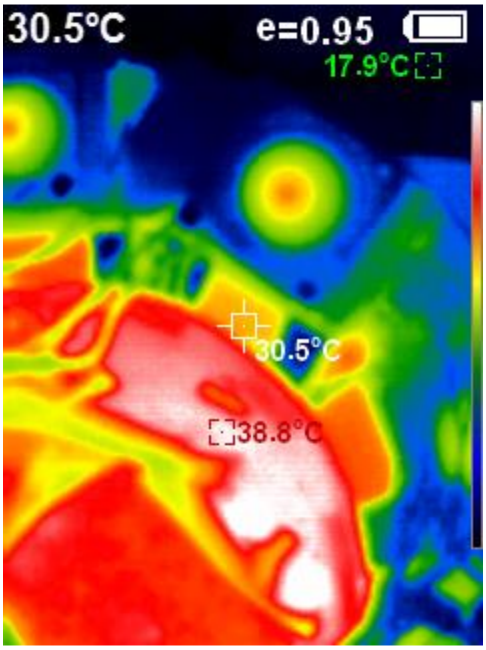

Figure 4.20 - Thermal image of the “A” saddle, indicating 30.5C (aimed at the rubber strip). This saddle is colder than the “OLD” saddle.

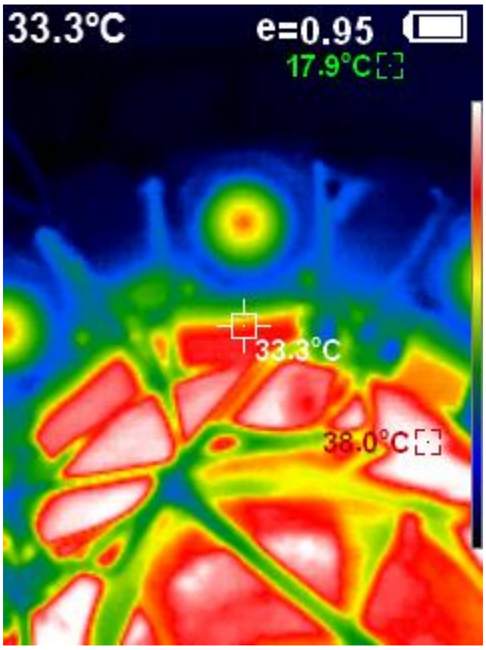

Figure 4.21 - Thermal image of the “B” saddle, indicating 33.3C

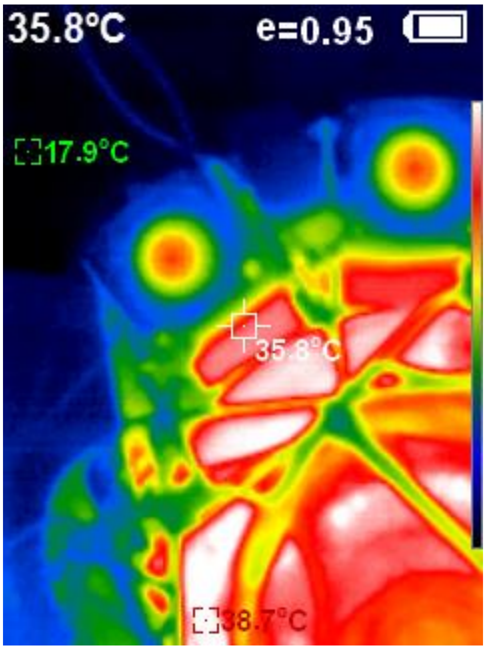

Figure 4.22 - Thermal image of the “C” saddle, indicating 35.8C

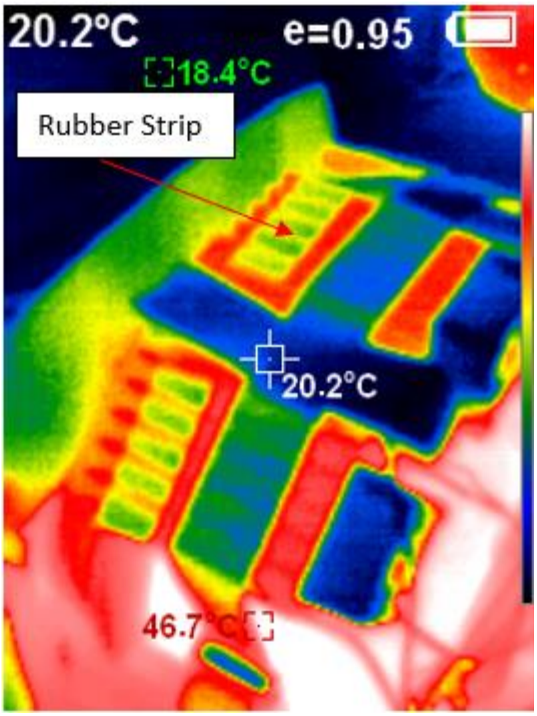

Figure 4.23 - Thermal image of the foam insulation indicating 20.2C (close to the air temperature)

Whilst observing, a series of thermal images (Figure 4.19 to Figure 4.23) are taken to analyse the temperature distribution across various saddles, labelled "OLD," "A," "B," and "C." These images are captured to provide insight into the performance and efficiency of the (TEG) system (Riffat & Ma, 2003).

The thermal image of the "OLD" saddle showed a temperature of 32.6°C, while the "A" saddle exhibited a slightly lower temperature of 30.5°C, as measured by aiming the thermal camera at the rubber strip. This suggests that the "A" saddle is colder than the "OLD" saddle. The "B" saddle displayed a temperature of 33.3°C, and the "C" saddle had the highest temperature at 35.8°C.

To summarise the saddle temperatures:

- “OLD” saddle: 32.6°C
- Saddle A: 30.5°C
- Saddle B: 33.3°C
- Saddle C: 35.8°C

The output voltages observed during prior experiments demonstrated a similar distribution, with Saddle A yielding the lowest output and Saddle C producing the highest output. This could be attributed (Jaziri et al., 2020) to either the internal design of the motor causing the "A" saddle to be colder or an issue with the saddle-to-motor interface's thermal contact.

Additionally, a thermal image is captured to illustrate the temperature distribution across the heat sink. In this particular trial, the fan voltage was deliberately reduced to allow the heat sink to warm up, thus making the temperature distribution more visible. The rubber strip's upper surface appeared cooler than the heatsink due to its contact with the colder surrounding air.

The relevance of these images to the research topic is as follows:

• Assessment of TEG Placement and Efficiency: These images help with providing data on the temperature differential created by the heat sink and motor arrangement, which is critical for TEG operation. Effective TEG placement could significantly impact the amount of power generated.

• Material Emissivity Corrections: The use of a tape with a consistent emissivity, helps ensure a more accurate thermal imaging, which is essential for precise temperature measurement and therefore critical to evaluating and improving the efficiency of the heat harvesting system.

• Comparison of Different Configurations: The reference to different TEGs (A, B, C) and the "OLD" designation is a direct comparison between different setups (given that it is identified that heat dissipation is not uniform across the body of the motor) This is vital for identifying the most effective configuration for heat harvesting.

• Heat Sink Performance: The fans and heat sink depicted are integral to creating a temperature differential by cooling one side of the TEG, and their performance directly impacts the amount of electricity generated by the TEGs.

• Manufacturing Integration: The practical setup shown is indicative of the challenges involved in integrating TEGs into manufacturing environments. Identifying issues with heat transfer efficiency, material compatibility, and the structural integrity of the setup can guide the design of scalable heat recovery systems for industrial applications.

In summary, the images provide insights into the practical experimentation and testing phase of research into heat harvesting using TEGs'. Each component and measurement is part of a larger effort to optimise a system that can effectively convert waste heat into electrical energy, contributing to the net-zero energy goal in manufacturing settings.

5. UPCYCLING, ENERGY HARVESTING AND THE CULMINATION

5.1 Introduction.

As discussed in Chapter 1 and Chapter 2 (subsection 2.1.1), this study hypothesizes that the integration of Design for Excellence (DFX) principles can be used as a carbon reduction strategy towards achieving net zero in manufacturing environments through the use of upcycling and energy harvesting (via a combine RF and TEG device) (Liu et al., 2015). In this section, a case study is analysed to aid in evaluating the hypothesis using the methodology proposed. For this, the data will be collected from an energy-harvesting hybrid RF-TEG harvester mated to a typical an AC motor – as would be typically found in manufacturing environments. The case study is then conducted to demonstrate the use of upcycling, where an automotive headlight is re-manufactured with a modular design that uses affordable and interchangeable parts (Lindkvist, Sundin and Sakao, 2019).

The research questions that guide this section of the study are as follows:

1. How can DFX principles be integrated into manufacturing environments to reduce carbon emissions?

2. How can upcycling be used as an effective approach towards achieving net-zero?

3. How can energy harvesting be used to reduce carbon emissions in manufacturing environments?

The study uses a mixed-methods approach, incorporating both quantitative and qualitative research methods. Data is analysed using statistical techniques and presented in a clear and concise manner (Santos et al., 2017).

This study contributes to the current knowledge on how to reduce carbon emissions in manufacturing environments. The findings offer practical solutions to industries aiming to reduce their carbon footprint and ultimately, achieve net-zero targets (Fankhauser et al., 2022).

Upcycling is the process of taking an existing material or product and reusing it to create a new, higher-value product (Oyenuga et al., 2017). This process can have a significant impact on reducing the carbon footprint associated with the production of new materials and products. The environmental benefits of upcycling can be quantified through a life-cycle assessment (LCA), which is a tool used to evaluate the environmental impacts of a product or service throughout its entire life cycle, from the extraction of raw materials to the disposal of the final product. In simple terms repairing/reusing existing products and infrastructure (Lindkvist, Sundin and Sakao, 2019) is a crucial strategy for achieving net zero emissions (Fankhauser et al., 2022) and a more sustainable future. A study by the National Renewable Energy Laboratory (NREL) found that recycling aluminium cans can save 95% of the energy required to produce new cans from raw materials (Green, 2007). These examples demonstrate the significant potential for carbon reduction through the implementation of upcycling, recycling, and reuse. A transition to a circular economy could result in economic benefits up to $4.5 trillion (Accenture, 2015) and reduce greenhouse gas emissions by up to 9.3 billion tonnes ($CO2$ equivalent) by 2050 (Ellen Macarther Foundation, 2019). This is because the production of new products requires significant energy and resources, leading to higher carbon emissions. In contrast, repairing and maintaining existing products can greatly reduce these emissions.

Research also suggests that repairing products can prolong their lifespan, reducing the need for constant replacement and reducing waste (Scott and Weaver, 2014). This benefits not only the environment but also the economy by decreasing the need for costly new production. Furthermore, the circular economy can bring significant job opportunities, as the repair and maintenance sector is often more labour-intensive than the production of new products (Van Ewijk, 2018).

The Embodied energy of the product also should be considered, such that products with high embodied energy are kept (ideally) in use for as long as possible, while products with low embodied energy being the ones that are considered for replacement with more efficient and sustainable options (Cooper and Gutowski, 2017).

Furthermore, research shows that the repair and remanufacturing of products can greatly reduce the environmental impacts associated with the production of new products. A study by Zhang et al. (2020) found that repairing and remanufacturing products can reduce the environmental impacts associated with production by as much as 90%. Similarly, a study by Guinée et al. (2011) found that the circular economy can reduce greenhouse gas emissions by up to 40%.

However, it's important to note that repairing should be done in a way that is economically and environmentally sustainable, so it's crucial to make sure the repair is not more costly than a new product. Also, regulations and policies should be in place to ensure that products are designed for repair and that repair services are accessible and affordable (Ellen MacArthur Foundation, 2017).

Repairing existing products and infrastructure is a crucial strategy for achieving net zero emissions and a more sustainable future. It can provide significant economic and environmental benefits while reducing waste and emissions. To ensure the repair is sustainable and cost-effective, regulations and policies should be in place to ensure products are designed for repair and repair services are accessible and affordable. It is important to note that in addition to repairability, other aspects of design that could reduce carbon footprint include designing for energy efficiency, weight reduction, and use of sustainable materials. – this ties in with the DfX paradigm discussed in chapter 2. By incorporating relevant DFX principles, organisations can optimise their products for environmental performance, reducing their energy use and carbon footprint (Alkadi et al., 2013; Seow et al., 2016). In addition to DFX, organisations can use ISO 14001 Environmental Management Systems (EMS) to efficiently manage their carbon footprint. An EMS provides a framework for organizations to identify, manage, and improve their environmental performance. A study by the International Journal of Environmental Research and Public Health found that organisations that implement an EMS have lower carbon emissions and energy use compared to those that do not (Hui et al., 2001).

5.2 The use of the United State Dollar ($) Justification

The calculations presented in thesis are presented in US dollars as the base currency. This is for the reasons that, the US dollar is a widely recognised and accepted currency, which allows for easy comparison of costs and benefits across different countries and regions. It is often used as a reference currency in international trade, financial markets, and economic analysis (Eichengreen, 2011). By presenting the calculations in US dollars, this thesis ensure that the results can be more easily understood and compared by a global audience.

The US dollar has historically been a relatively stable currency, reducing the impact of exchange rate fluctuations on the cost-benefit analysis (Eichengreen, 2011; Krugman et al., 2015). This stability can help to ensure that the results of the analysis remain relevant and accurate over time. A plethora of data sources, including international organisations, research institutions, and industry databases, provide cost and environmental impact data in US dollars, thus simplifying data collection, analysis, and reporting (World Bank, 2021).

Furthermore, many stakeholders, including investors, policymakers, and researchers, are familiar with the US dollar and its value, making it a convenient choice for presenting financial information. Using US dollars can help ensure that the results are easily understood and comparable by a wide range of stakeholders (IMF, 2021). Finally, many Life Cycle Assessment (LCA) studies and cost-benefit analyses in the field of energy harvesting and environmental management use the US dollar as the currency unit for presenting their results (Huijbregts et al., 2017; Ingwersen et al., 2022; McKinnon et al., 2007). By following this convention, it is ensured that the presented results are consistent with the existing literature and can be easily compared with other studies.

5.3 Metrics, Results & Justification

A brief overview of the most prevalent mathematical models is discussed below with their limitation. Given that the study for this assessment is going to be based on the implementation/review on a vehicle headlight, consideration will be given to the model that will serve best to yield objective results for the case study.

5.3.1 Life Cycle Assessment (LCA)

This tool is used to measure the environmental impact of a product or service over its entire life cycle, from raw material extraction to disposal. LCA is considered one of the most reliable models for carbon reduction due to the fact that it takes into account all the stages of a product's life cycle, from raw material extraction to disposal. It provides a comprehensive view of the environmental impact of a product or service, including carbon emissions (Guinée et al., 2002).

5.3.1.1 Types of LCA:

a) Attributional LCA: Attributional LCA aims to describe the environmentally relevant physical flows to and from a product system, providing a static snapshot of the environmental burdens associated with a product (Curran, 2013). It is typically used for product comparisons, eco-labelling, and environmental management.

b) Consequential LCA: Consequential LCA focuses on the potential environmental consequences of a decision, such as changes in production systems or adoption of a new technology (Ekvall & Weidema, 2004). It identifies the cause-effect relationships between a decision and its environmental impacts and is more suited for policy-making and decision support.

5.3.1.2 System boundaries:

The system boundaries define the scope of the LCA study, determining which processes, inputs, and outputs are included in the assessment. Examples of system boundaries are:

1. Cradle-to-grave: As previously mentioned, this approach considers the entire life cycle of a product from raw material extraction to its disposal at the end of its useful

life.

2. Cradle-to-gate: This LCA type focuses on the life cycle stages from raw material extraction up to the point where the product leaves the production facility (the "gate"). It includes raw material extraction, production, and manufacturing processes but excludes distribution, use, and end-of-life stages. This approach is often used by manufacturers to assess the environmental impacts of their production processes.

3. Gate-to-gate: Gate-to-gate LCA focuses on the environmental impacts of a specific process or set of processes within a product's life cycle. It does not cover the entire life cycle of a product, but rather, evaluates the impacts of a particular segment, such as manufacturing, transportation, or recycling.

4. Cradle-to-cradle: This LCA type emphasises the concept of a closed-loop, where waste materials are recycled or upcycled into new products, thus minimizing waste and resource depletion. Cradle-to-cradle LCA takes into account raw material extraction, production, use, and recycling or upcycling processes, considering that products are designed for continuous cycles of use and reuse.

5. Attributional LCA: This LCA type is focused on quantifying the environmental impacts of a product or system based on a snapshot of its life cycle stages. It assigns environmental impacts to specific processes and inputs within the system, providing a static view of the environmental performance of a product.

6. Consequential LCA: Consequential LCA aims to identify and assess the environmental impacts of decisions or changes in a product's life cycle, taking into account the potential consequences of these changes. It considers both the direct and indirect effects of decision-making, including the impacts on other systems, processes, or products.

Each of these LCA methodologies serves different purposes and can be used depending on the goals and scope of the assessment. They provide insights into various aspects of a product's life cycle, allowing decision-makers to understand the environmental impacts of their products and identify opportunities for improvement.

5.3.2 Input-Output Analysis (IOA)

Simply put, this technique is used to model the interdependence of various sectors of an economy, allowing for the assessment of the carbon emissions impact of a particular sector. IOA can help identify opportunities for reducing carbon emissions in supply chains. This is largely due to the fact that it provides a detailed picture of the interdependence between different sectors and allows the calculation of indirect emissions from the production of inputs to the final production process (Zhang et al., 2020). This information is valuable in identifying the most significant contributors to carbon emissions in a supply chain and can help companies prioritize their efforts to reduce emissions (Bocken and Allwood, 2012). While not as product-specific as LCA or Carbon Footprint Analysis, IOA has some advantages in assessing the environmental impacts of products and services.

1. Economy-wide analysis: IOA provides a macroeconomic perspective on environmental impacts by analysing the interdependencies between different sectors of an economy (Suh, 2004). This allows for the identification of indirect environmental impacts related to the production, use, and disposal of a product, such as a halogen headlight.

2. Resource use and emissions: IOA can provide information on the use of resources and emissions associated with a product throughout its life cycle, thus offering insights into the environmental performance of a product (Hendrickson et al., 2006).

3. Integration with LCA: IOA can be combined with LCA to create a hybrid life cycle assessment approach. This can help overcome some of the limitations of both methods, such as the truncation error in LCA and the lack of product specificity in IOA (Suh & Huppes, 2005).

4. Data availability: IOA uses national economic data, which is often readily available

and can be used to assess the environmental impacts of products and services in different countries (Miller & Blair, 2009).

However, IOA has some limitations when compared to LCA and Carbon Footprint Analysis:

1. Product specificity: IOA is less suited for assessing the environmental impacts of a specific product, such as a halogen headlight, as it focuses on the broader interdependencies between economic sectors.

2. Aggregation: IOA results are generally presented at the sector level, which may not capture the detailed environmental performance of individual products or processes.

3. Geographic limitations: IOA relies on national economic data, which may not accurately reflect the specific production, use, and disposal conditions of a product in different countries or regions.

In summary, while IOA is not as well-suited for product-specific assessment as LCA or Carbon Footprint Analysis, it can still provide valuable insights into the environmental impacts associated with a product's life cycle, particularly when combined with other assessment methods.

5.3.3 Circular Economy Model:

The Circular Economy Model is based on the principles of waste reduction, resource efficiency, and closed-loop production systems. It seeks to minimise the extraction and use of finite resources, reduce waste, and increase the recycling and reuse of materials (Ghisellini et al., 2016). This approach provides a framework for reducing emissions by minimizing the use of energy-intensive processes and promoting the reuse of materials and resources (Stahel, 2010). By minimizing waste and increasing the efficiency of resource use, the Circular Economy Model can help reduce the carbon footprint of production processes and products (Lieder et al., 2018).

5.3.4 LCA Justification

In conclusion, the LCA, IOA, and Circular Economy Models are considered to be effective for carbon reduction calculations as they provide comprehensive, systematic, and transparent frameworks for understanding and reducing carbon emissions. While each approach has its own strengths and limitations, these models provide valuable information for companies and policymakers looking to reduce emissions and contribute to a more sustainable future. Ultimately, it is considered that LCA will be the most suitable for this study after considering the limitations within the other models that exist.

The reasons for choosing an LCA case study are as follows:

1. Holistic approach: LCA allows for a comprehensive and systematic evaluation of the environmental performance of a product by considering all stages of its life cycle, from raw material extraction to end-of-life disposal or recycling (ISO, 2006). This holistic approach helps to identify potential environmental hotspots and avoid burden shifting between life cycle stages.

2. Comparability: LCA provides a standardized framework for comparing different products or design alternatives, enabling decision-makers to make informed choices about environmentally preferable options (Rebitzer et al., 2004).

3. Quantitative analysis: LCA offers a quantitative approach to assess the environmental impacts of a product, which helps in identifying specific areas for improvement and setting benchmarks for performance (Finnveden et al., 2009).

4. Versatility: LCA can be applied to a wide range of products and sectors, making it suitable for various case studies, including the halogen headlight (Klöpffer and Grahl, 2014).

5. Decision-making support: LCA provides valuable information for decision-makers in product development, policy-making, and other fields by highlighting the environmental trade-offs associated with different choices (Baumann and Tillman, 2004).

6. Broad recognition: LCA is recognized and supported by various organisations, including the International Organization for Standardization (ISO), which has developed a series of standards (ISO 14040 and 14044) to guide LCA methodology and practice (ISO, 2006).

5.3.5 The LCA selection, The system boundary, and the scope of the LCA research

For this study the two types of LCA are considered to determine the best fit. Given the considerations and merit for each discussed in 5.3.1, it is considered that the best fit for this study is the 'cradle-to-grave' system boundary for both the halogen headlight upcycling and the RF-TEG trials, as it encompasses the entire life cycle of the products, from raw material extraction to end-of-life disposal or recycling.

The scope (system boundary) of the LCA research for the case study subject, given the use of the cradle-to-grave system boundary, encompasses the entire life cycle of the product, from raw material extraction to end-of-life disposal or recycling.

The stages of the life cycle are listed in chronological order below, with an explanation of what is included in each stage.

1. Raw Material Extraction: The extraction of raw materials needed for the production of the headlight, including metals, plastics, and other components.

2. Material Processing: The transformation of raw materials into semi-finished or finished materials suitable for use in manufacturing.

3. Manufacturing: The production processes, including the assembly of all the components.

4. Distribution: The transportation and distribution from the manufacturing facility to the end user.

5. Use: The usage phase of during its expected lifespan, which mainly considers energy consumption.

6. End-of-Life Treatment: The disposal, recycling, or upcycling after its useful life has ended. This includes waste management processes and the potential environmental impacts associated with them.

By using the cradle-to-grave system boundary, the LCA research aims to provide a comprehensive assessment of the environmental impacts associated with the case study subject throughout its entire life cycle.

The LCA frameworks that have informed this work are ISO 14040 and 14044. These standards are briefly explained below:

1. Goal and Scope Definition: Clearly defining the purpose, target audience, and intended application of the LCA study. For this study, establishing the functional unit as (one headlight with a lifespan of 5 years) and determining the system boundary (cradle-to-grave).

2. Life Cycle Inventory (LCI) Analysis: Collecting the data on inputs (raw materials, energy – actual or from a credible source) and outputs (emissions, waste - actual or from a credible source) related to the product systems. This data being as comprehensive as possible and consistent with the system boundary defined in step 1.

3. Life Cycle Impact Assessment (LCIA): Evaluation of the potential environmental impacts associated with the inputs and outputs identified in the LCI. This step involves selecting relevant impact categories (in this case - climate change, resource depletion), classifying inventory data into these categories, and characterising the magnitude of the impacts.

4. Interpretation: Analysis of the end results of the LCI and LCIA, identifying significant issues and drawing conclusions. This allows the practitioner to assess the robustness and reliability of the results, considering data quality, uncertainties, and

sensitivity analysis. Based on the interpretation, provide recommendations for improvements or decision-making.

The LCA framework has served as the foundation for conducting a comprehensive and reliable assessment of the environmental impacts associated with the upcycling of the presented halogen headlight. The above steps have also ensured that the LCA study is conducted systematically, providing valuable insights to support decision-making and potential improvements in product design or policy.

Furthermore, it is determined that for both studies, the system boundaries/scope will be in line with Cradle-to-grave. Figure 5.1 portrays a typical outlook for such scope.

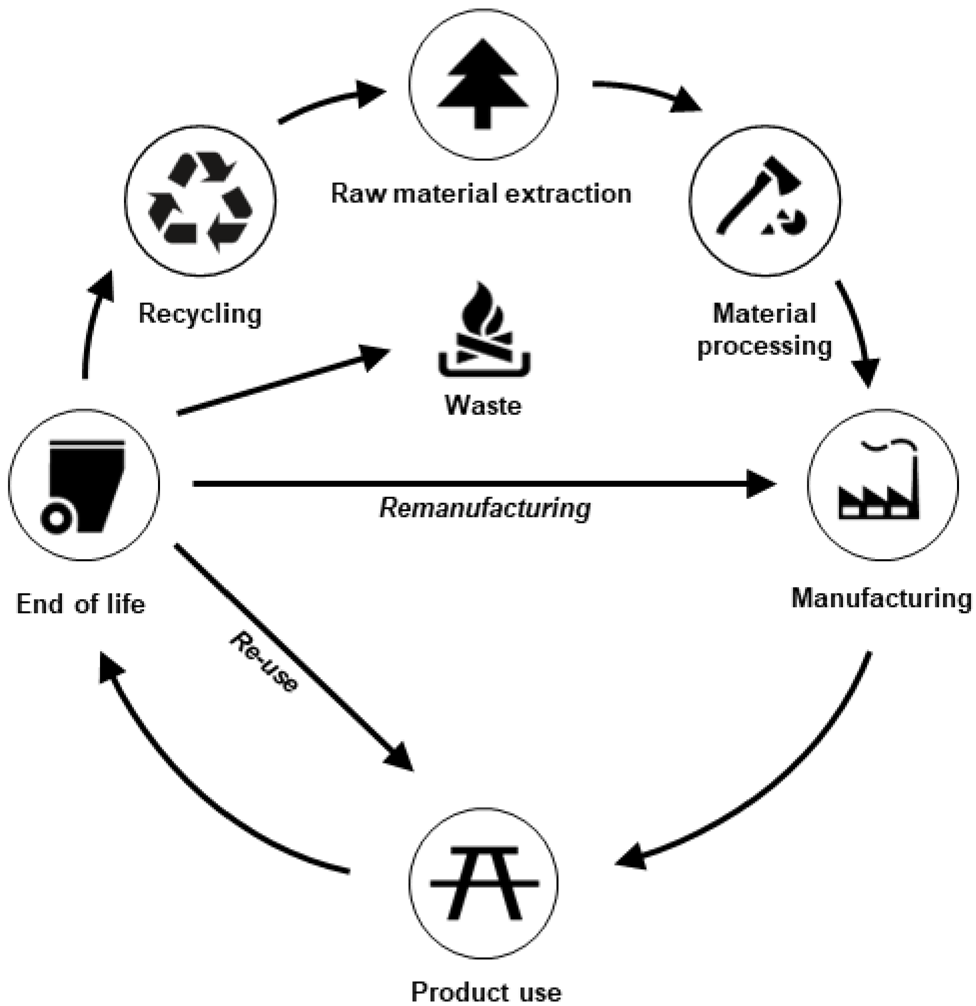

Figure 5.1 - System boundaries for Cradle-to-Grave

5.4 Radio Frequency – Thermoelectric Harvesting

Literature suggests that Radio Frequency (RF) energy harvesting, in particular, has emerged as a promising technology, enabling the conversion of RF waves into usable electrical energy. Exploratory laboratory trials suggest that a lot of work still needs to be done to generate useful substantial energy from RF alone. This chapter explores the qualitative and quantitative analysis of RF-thermoelectric harvesting, a specific technique that utilises thermoelectric materials to generate electricity directly from heat produced by RF waves. A detailed examination of the underlying principles and design considerations of this technology provides a comprehensive understanding of its potential applications and limitations. The results of this literature analysis are expounded, including experimental data and theoretical models, to assess the performance of RF-thermoelectric harvesting and identify areas for further research and development. By delving into the intricacies of this cutting-edge technology, the hope is to contribute to the ongoing efforts to develop efficient and sustainable energy solutions for the future.

5.4.1 Radio Frequency – Thermoelectric Harvesting Results and discussion

From the Energy Harvesting frontier, the data is collected from an energy-harvesting hybrid RF-TEG harvester mated to a typical AC motor as commonly used in manufacturing environments. The energy harvesting hybrid RF-TEG harvester consists of a printed circuit board with an RF energy harvesting module and a TEG energy harvesting module. The chosen RF energy harvesting module operates at a frequency of 2.4 GHz (for reasons that have been discussed in chapter 3 of this thesis), while the TEG energy harvesting module generates power from the temperature difference between the hot and cold sides of the TEG module. The data is collected over a period of 1 hour, and the results presented in Table 4.1.

It is worth noting that under load (when in use), DC motors typically produce more heat than AC motors in manufacturing. Luo, Ye and Rashid (2005) compares the heating effects on AC and DC motors and identifies that the DC motor produced more heat than the AC motor. Similarly, (Rahman et al., 2011) identifies that permanent magnet synchronous DC motors produce more heat than induction AC motors.

Further research has shown that the internal resistance and inductance of DC motors lead to more heat generation under load. Xuan et al. (2017) studied the impact of brushless DC motors on heat transfer in refrigeration compressors and found that the DC motor generated more heat due to its higher inductance and internal resistance. Similarly, Gerber et al. (2018) used simulation and experimental research to compare AC and DC motors and found that the DC motor produced more heat due to its internal resistance.

In contrast, AC motors can generally operate at lower temperatures and have better thermal stability under load. Rajini et al. (2022) compared permanent magnet synchronous AC motors and induction AC motors for industrial applications and found that the AC motors had better thermal stability and could operate at lower temperatures.

Research shows that AC motors are commonly used in manufacturing environments due to their reliability, efficiency, and lower maintenance costs compared to DC motors (Kumar, 2018; Chang, 1994; Goetzler et al, 2013; McCoy et al, 1990; Errigo et al., 2022). AC motors offer several advantages, including higher efficiency, lower maintenance requirements, and longer lifespan. While DC motors may offer better speed control and higher torque at low speeds, they also require more maintenance and can be more expensive to operate (Kumar, 2018; Goetzler et al, 2013; Sedef et al., 2012).

There is a clear consensus among researchers that DC motors tend to generate more heat than AC motors when under load due to the internal resistance and inductance of DC motors. Although the research presented in this thesis focuses on observations from a typical AC motor commonly found in manufacturing environments, it is important to note that any energy generated from the reduced heat output of AC motors could be significantly improved by utilizing DC motors, which emit more heat that can be harvested and converted into useful energy. Rahman et al. (2011) identifies that AC motors are more energy-efficient and produced less noise and heat compared to DC motors. Similarly, Kumar and Kumar (2020) and Choudhary et al. (2017) compared the performance of DC and AC motors for a solar-powered water pumping system and found that AC motors were more efficient and reliable for industrial applications.

Therefore, while the specific observations in this thesis relate to AC motors, it is still worth considering the potential benefits of utilising DC motors for energy harvesting purposes in manufacturing environments where its merited.

The literature review has helped in guiding evidence to support the recommendations for best practices in batch manufacturing detailed in Chapter 6.

The build implementation/build of the Energy Harvesting is based on a 0.3 horsepower AC motor typically used in a manufacturing environment. Its use can be diverse, as these motors are versatile and can be employed in various applications to meet different needs. The AC motor's role in a manufacturing setting is typically characterized by its ability to efficiently convert electrical energy into mechanical energy, enabling it to power machines and equipment used in the production process (Kreith and Goswami, 2007). Another application for a 746-watt AC motor in a manufacturing environment is the operation of smaller machines and tools, such as drills, lathes, and milling machines. These machines require precise control and a consistent source of power to ensure accurate and efficient production (Kostić, 2010). The reliability and performance of AC motors make them well-suited for these applications, as they can maintain constant speed and torque under varying load conditions (Reza, Islam and Mekhilef, 2014). Another typical application for this type of motor is in manufacturing is powering conveyor systems, which are an essential component of many production lines. Conveyor systems transport materials, parts, or finished goods from one location to another, streamlining the manufacturing process and increasing efficiency (Zylstra, 2015; Azizi et al., 2018). The use of AC motors in conveyor systems enables precise control over speed and torque, ensuring that materials are moved smoothly and reliably throughout the production process (Boldea & Nasar, 2002). The results obtained will be discussed and relevant quantitative analysis put forward. It should be noted that the results from the RF component of this build have been modelled first before inputting actual results forward for the process of validating the simulated data. However theoretical simulations suggest that the energy harvested can be further improved using a voltage multiplier (Yuan et al., 2015) which has been employed on both elements of the device. Additionally, it is apparent from literature reviewed that the bandwidth from which energy has been harvested so far is not the most energy rich, thus consideration will be given to designing further filter antenna with the intention of exploring a different bandwidth through use of a signal generator for validation purposes.

Elements are combined into a comprehensive guideline and have been vital towards the aims and objectives that this thesis started with.

It should be noted that these processes and guidance are not limited to batch manufacturing environments alone and can be applied to other forms of manufacturing where the by-products might be different, but this thesis sets the precedence in the fact that the manufacturing sector in general produces waste product that can be re-utilised. This thesis has focussed on batch manufacturing due to the ability of elements being able to be validated within the resources of the University of Hertfordshire manufacturing/engineering laboratories that present/depict a typical batch manufacturing layout.

The gallery below shows step-by-step build process of the RF-TEG Harvesting device.

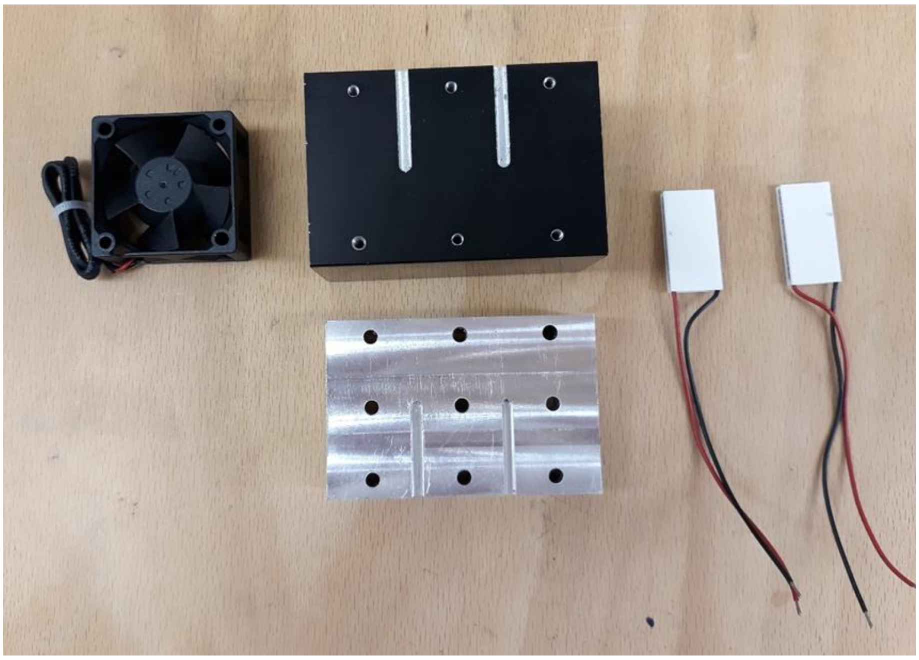

Figure 5.2 - Designed and built components of the Motor-RF Harvester

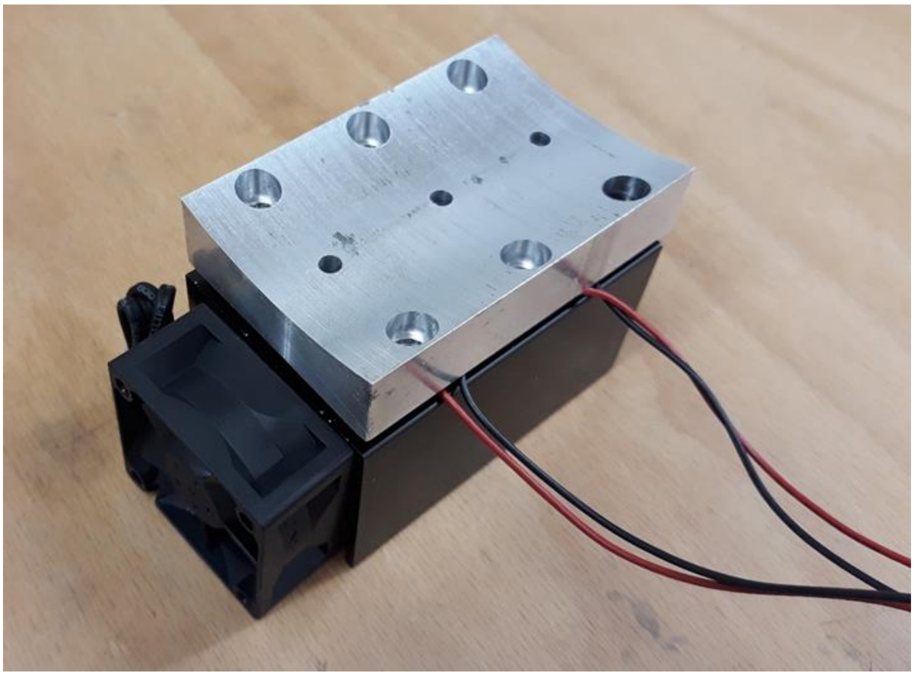

Figure 5.3 – Fully assembled Motor-RF Harvester

Figure 5.4 - AC Motor utilised in setup (specifications in Appendix J; MM Engineering Services 2023)

During the process of initial setup on a test bench over 100mV was achieved after the motor ran for less than five minutes. The full setup and continual testing/validation will continue and forms significant part of the future work for this thesis.

Table 5.1 – Energy harvesting results

Time (minutes)	RF Power (μV)	TEG Power (V)	Total Power (V)
5	80	-	0.00008
10	80	-	0.00008
15	80	-	0.00008
20	80	-	0.00008
25	80	-	0.00008
30	80	-	0.00008
35	80	4.31	4.31008
45	80	4.96	4.96008
50	80	5.26	5.26008
55	80	5.53	5.53008
60	80	5.68	5.68008

The results show that the total power generated by the energy-harvesting hybrid RF-TEG harvester increased over time, from 4.3V at the start of the test to 5.68V after 1 hour of operation. The TEG module generated most of the power, with an average of 5.1V, while the RF module generated an average of 0.005V. The total power generated is relatively low, but it is a promising technology that could be used to power low-power devices in manufacturing environments – to elaborate, powering low-voltage sensors or control circuits in typical manufacturing applications require low-voltage power. 5.1 volts can be used to provide the necessary power to these devices (Hidalgo-Leon et al., 2022), 5.1 volts can be used to charge small batteries or capacitors, which can then be used to power other devices or systems (Natarajan, 2018) or even act as a backup power source to keep critical systems or processes running until power is restored (Hordeski, 2020)., Small DC motors can operate on low voltage power, and 5.1 volts can be used to power these motors for various manufacturing processes (Moczala, 1998), many manufacturing processes require monitoring or displaying of data, and a nominal 5.1 volts can be used to power these small electronic displays for this purpose (Muccini, 2006).

5.4.2 Thermoelectric Stacking Results and discussion

From the above result, the idea of applying a multiplication factor that encountered minimum losses was considered, and thus the idea to stack (multiply) the TEG element of the harvester. Figure 5.5 – Figure 5.8 depict the new stacked TEG setup. The resulting outcome of this new setup is then shown in Figure 5.12 - Figure 5.14.

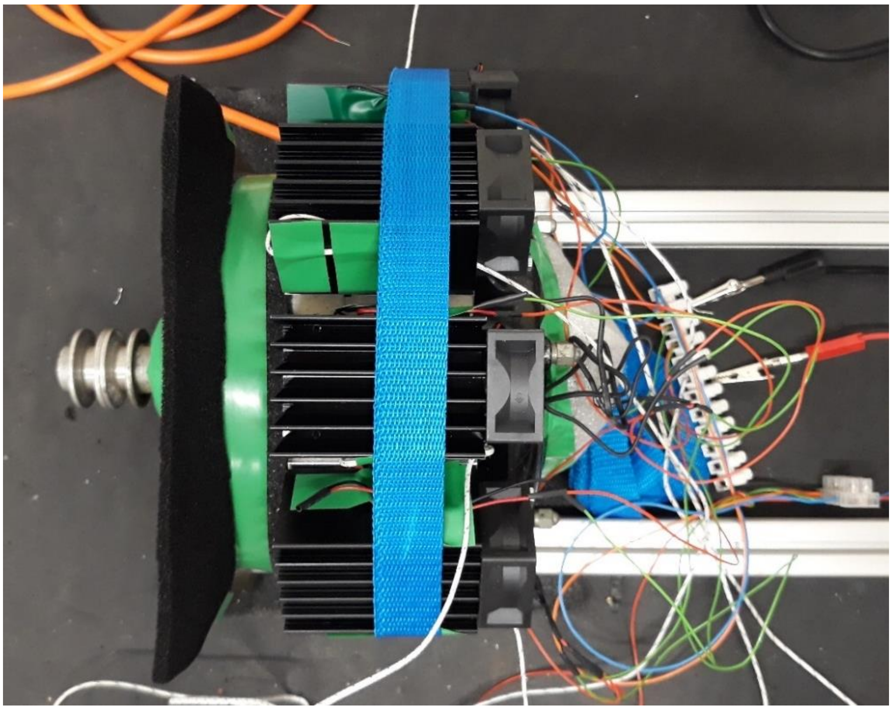

Figure 5.5 - View onto the top of the motor, showing the arrangement of the heatsinks and fans

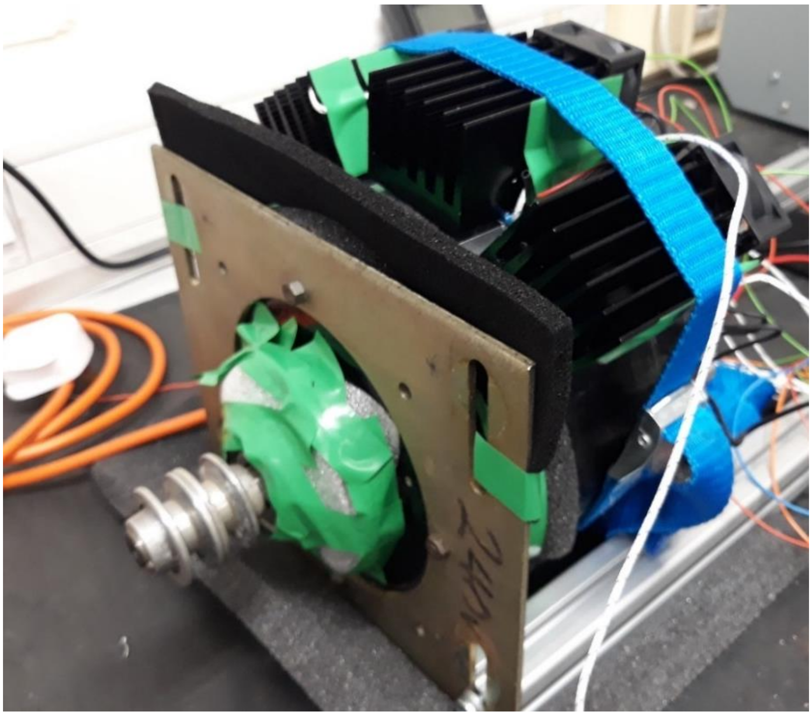

Figure 5.6 - View to the shaft end of the motor, showing the mounting plate with insulation behind

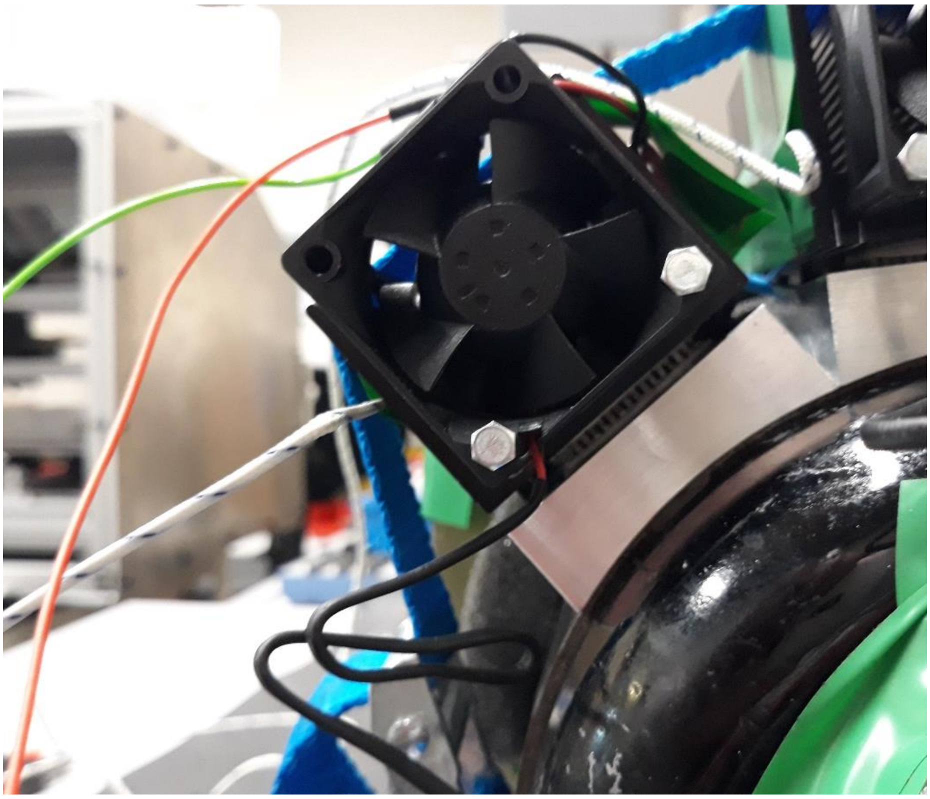

Figure 5.7 - Detail view of the fan, peltier and the aluminium thermal “saddle” connecting the Peltier to the outer surface of the motor

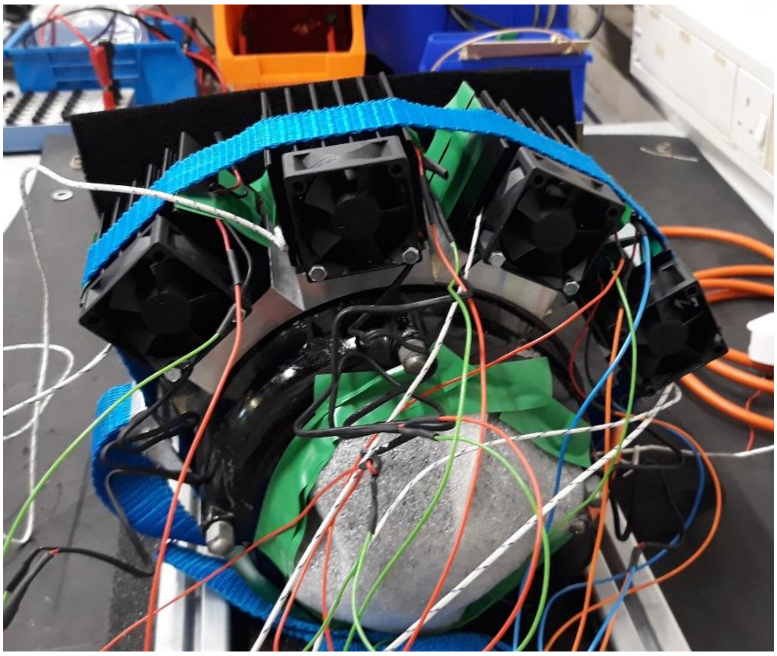

Figure 5.8 - View of the set of fans, TEG assemblies and the insulation at the rear of the motor

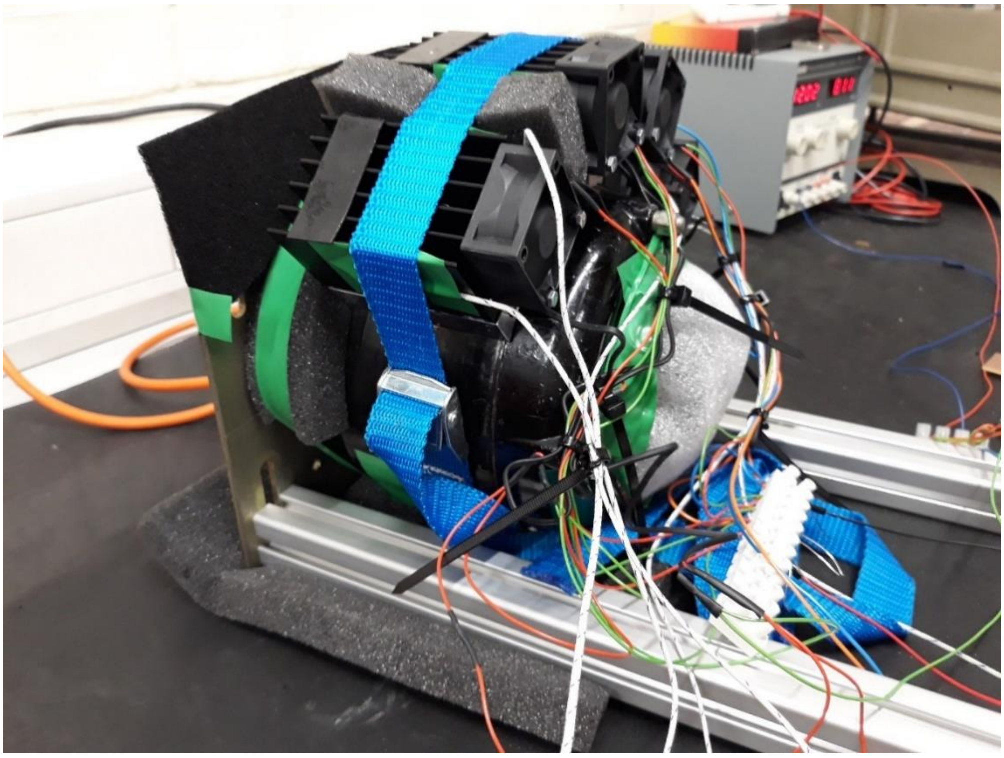

Figure 5.9 - General view of the Motor with TEG assemblies

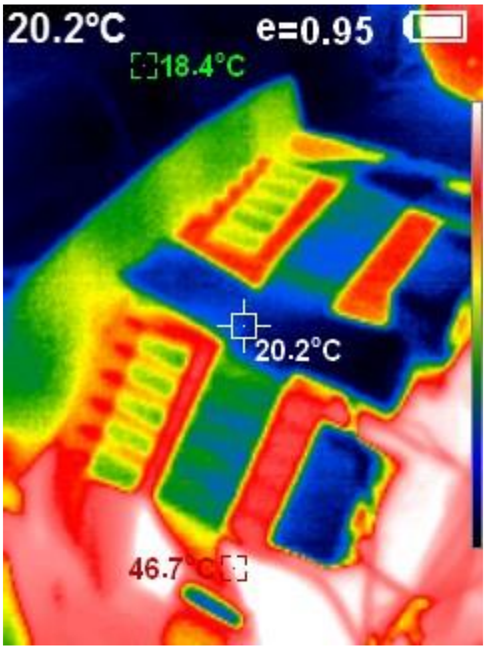

Figure 5.10 - Thermal image showing the heatsink temperature distribution

In the trial depicted in the thermal image (Figure 5.10), the fan voltage is reduced so that the heatsink becomes warm, in a bid to allow the temperature distribution become more visible. The rubber strip upper surface is cooler than the heatsink due to contact with colder air.

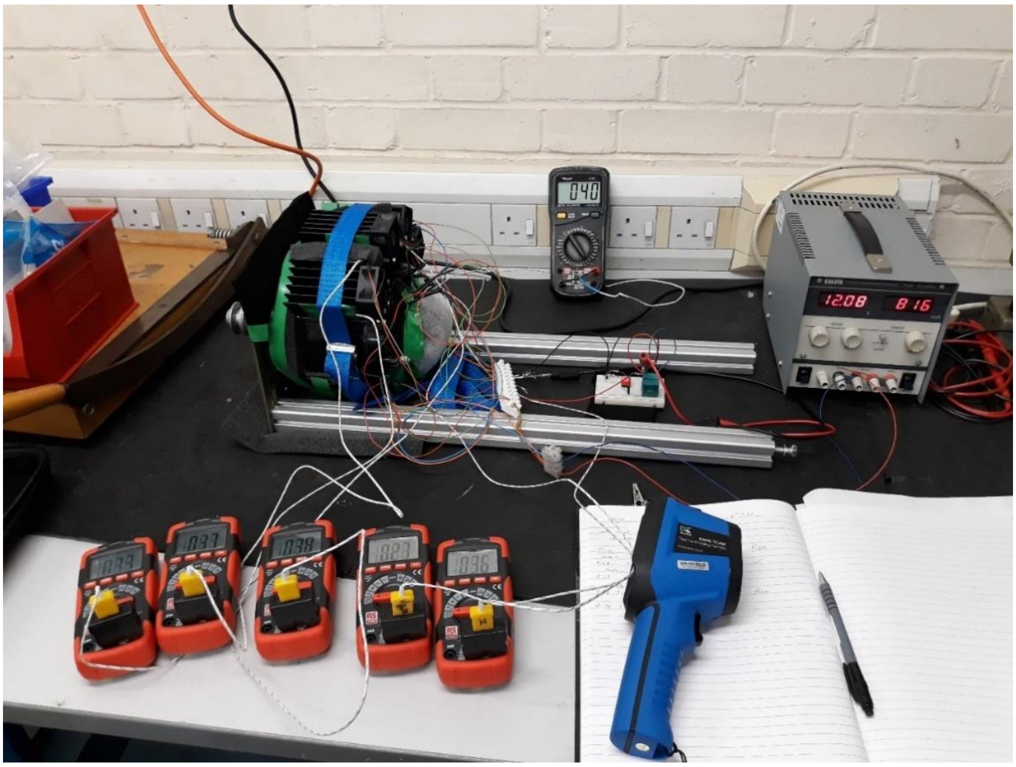

Figure 5.11 – View of the complete test rig setup

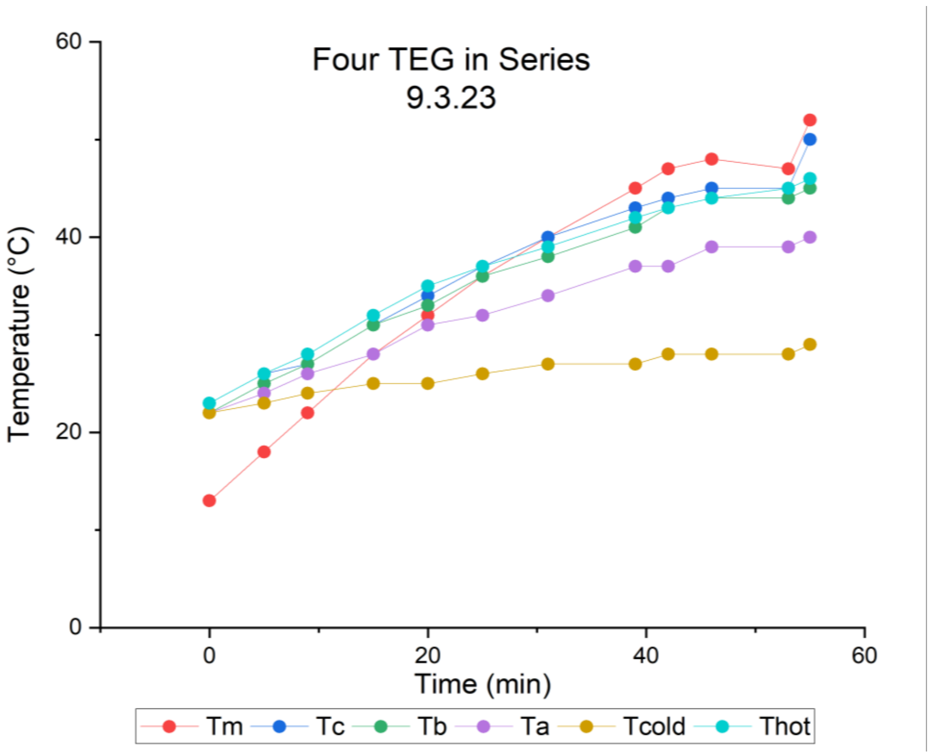

Figure 5.12 - Recorded temperature results for four TEG in series

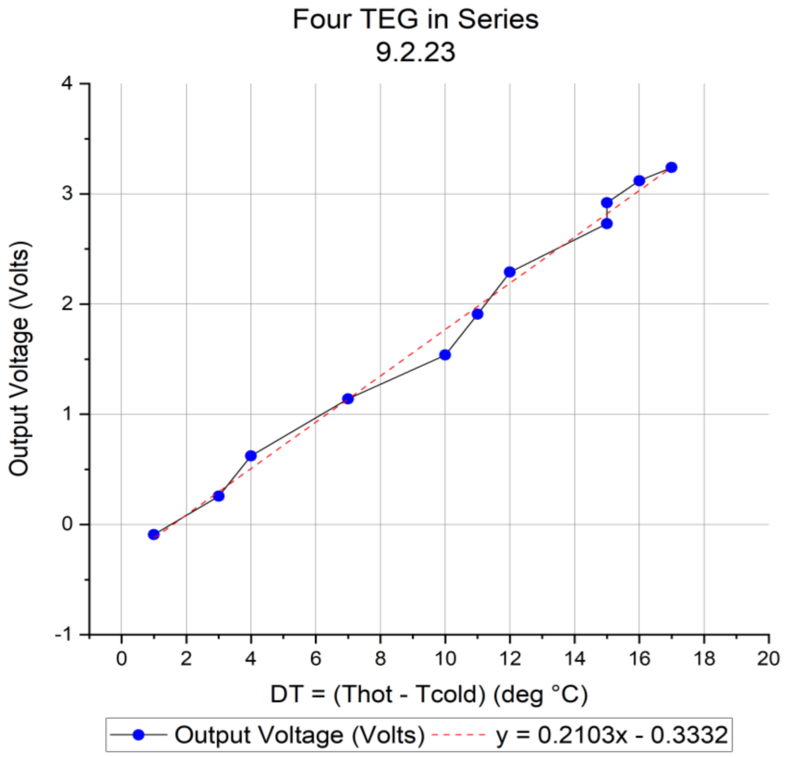

Figure 5.13 – Output voltage for four TEG in series

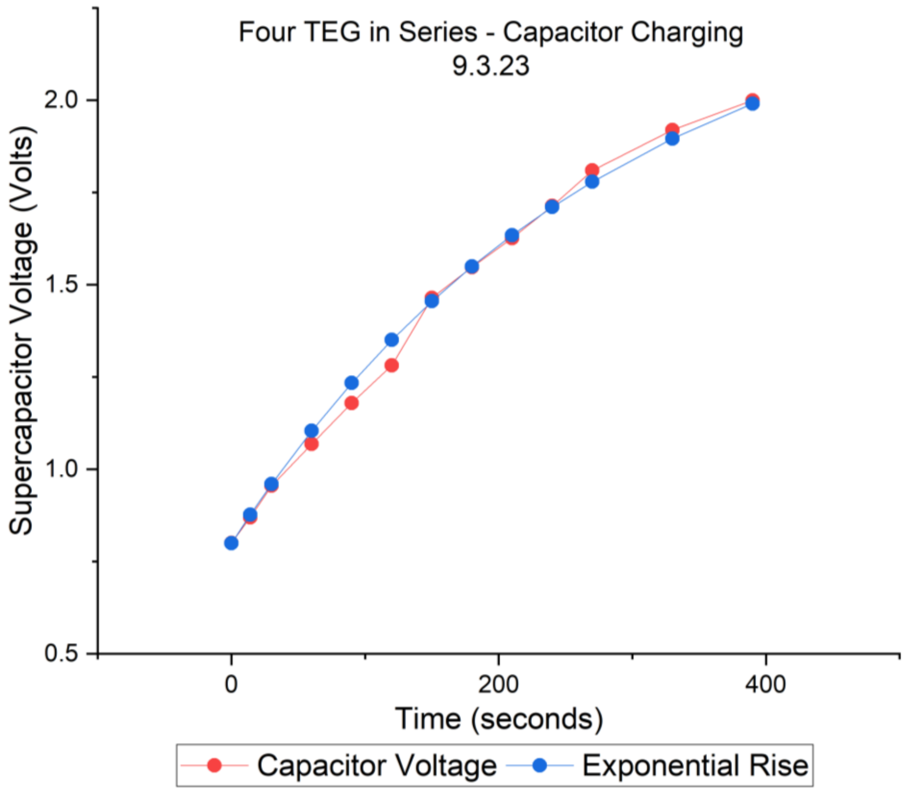

Figure 5.14 - Supercapacitor voltage for four TEG in series

The generated volts are thus trialled in the charging of a supercapacitor.

The obtained results/raw data as shown in Table 5.2 will now be used to run some quantitative analysis. This quantitative analysis will rely on elements of LCA as discussed earlier.

Table 5.2 – Raw data from four TEG setup

Variable	**Value**	**Unit**
Offset	0.8	(dimensionless multiplier)
Amplitude	1.59	V
Torr	282	Pa
Vin	3.24	V
Vstart	0.8	V
Rseries	200	Ω
Max current	0.0122	A
TEG resistance	20	Ω
Matched load	20	Ω
Max voltage	3.24	V
Matched power output	0.13122	W

As shown above, the maximum current generated by the TEG stack setup is 0.0122A, thus, to calculate the power generated by the TEG as a factor of the power of the motor one considers the following. Making reasonable assumption that the TEG-integrated AC motor results in a conservative 0.5% energy savings. Given the 1/3 horsepower motor, its power output is approximately 249 watts (Kreith and Goswami, 2007).

The power generated by the TEG (in watts) can be calculated using equation (5.1):

$$P_{TEG} = V_{TEG} \times I \tag{5.1}$$

Where P_{TEG} is the power generated by the TEG, V_{TEG} is the voltage produced by the TEG (3.24 volts), and I is the current in amperes (0.0122 A).

$$P_{TEG} = 3.24V \times 0.0122A \approx 0.0395W$$

The power of the motor, as calculated before, is 248.67 watts.

Comparing the power generated by the TEG to the power of the motor:

$$Power\ ratio = \frac{P_{TEG}}{Motor\ power} \times 100 \tag{5.2}$$

$$Power\ ratio = \frac{0.0395W}{248.67W} \times 100 \approx 0.0159\%$$

The power generated by the TEG (0.0395 W) is approximately 0.0159% of the power of the motor (248.67 W). This indicates that the energy harvesting from the TEG is relatively small compared to the motor's power. However, when compared to the initial exploratory run of a single TEG setup, the idea of a low voltage oscillator and multiplier circuit was to see what was possible within the limitations of the single TEG stack. As the voltage is only just above the threshold voltage for operation of silicon transistors or diodes, this results in only the small difference in voltage being available for power transfer. The result is that the losses are high. This drives the cost/benefit relationship into a poor region where this approach would only be justified for an extreme system.

With this new setup of 4 stacks (in series), the results have proved much better because the available voltage is much higher and so the available power can be exploited by simply having a switch-mode power supply circuit between the TEG stacks and a processor. The losses are now related more to switching times and inductor core losses including I^2.R losses in components. It might be expected that efficiencies in excess of 70% would be possible utilising available integrated circuits. The design problem is far easier and the cost/benefit relationship much more reasonable. With this in mind, a comprehensive cost-benefit analysis (CBA), which takes into account the costs and benefits of integrating TEGs into motor casings will be explored.

To conduct a comprehensive cost-benefit analysis for the integration of a thermoelectric generator (TEG) into an AC motor, one needs to consider the costs associated with the implementation of this technology and the benefits it provides in terms of energy savings and environmental impact reduction. The following assumptions and data will be used for this analysis:

1. The cost of TEG materials, fabrication, and integration into the AC motor
2. The potential energy savings from waste heat recovery
3. The reduction of carbon emissions and associated environmental benefits.

Assumptions:

1. The total cost for TEG materials, fabrication, and integration into the AC motor is assumed to be $200 (Li et al., 2021).
2. The annual operating hours of the motor are assumed to be 2000 hours per year (de Almeida et al., 2008).
3. The average price of electricity is assumed to be $0.12 per kWh (An et al., 2020).

Calculation:

1. Power generated by the TEG: 0.0395 W, as calculated in a previously
2. Annual energy generated by the TEG: 0.0395 W × 2000 hours = 79 Wh
3. Annual energy savings in kWh: 79 Wh / 1000 = 0.079 kWh
4. Annual cost savings: 0.079 kWh × $0.12/kWh = $0.00948

Considering the costs and benefits, the payback period can be calculated as follows:

$$Payback\ period = \frac{Initial\ cost}{Annual\ cost\ savings} = \frac{\$200}{\$0.00948} \approx 21{,}097\ years \tag{5.3}$$

Based on this analysis, the integration of a TEG into the AC motor appears to have a very long payback period, making it difficult to justify the investment from a purely economic standpoint. However, it is essential to consider the environmental benefits of waste heat recovery and carbon emissions reduction (Massetti et al., 2021). The actual cost-benefit analysis might vary significantly depending on the TEG's efficiency, material costs, and energy prices, among other factors.

From the perspective of LCA, a simplified, attributional LCA approach has been applied. As previously discussed, attributional LCA (ALCA) aims to describe the environmental impacts of a product system by allocating the inputs and outputs of the system to the functional unit of interest. It is a static, inventory-based approach that does not consider the consequences of changes within the system (Finnveden et al., 2009).

The justification for using this simplified, attributional LCA approach is that it is relatively easy to understand and apply, especially in cases where data is limited or specific information about the system is unavailable (for instance through the making of the TEG chip). The main goal of providing this LCA is to give a rough estimation of the energy consumption and carbon emissions reduction associated with the integration of a TEG into an AC motor.

However, it is important to note that a more comprehensive and accurate LCA would require a detailed analysis, considering various life cycle stages, environmental impact categories, and the potential consequences of changes within the system. In such cases, consequential LCA (CLCA) might be more suitable, as it aims to capture the potential environmental consequences of changes in a product system (Finnveden et al., 2009). CLCA can provide insights into the overall environmental impact of a product, considering market-driven effects and potential shifts in production and consumption patterns.

A high-level LCA overview is thus discussed below. This takes into account the integration of the (TEG) to the AC motor. Considering the various stages of the product life cycle, including raw material extraction, production, use, and end-of-life treatment. Due to the complexity of the LCA process, this high-level overview is calculated with reasonable assumptions and references included to show the source of these assumption. This is important because the TEG chip has not been manufactured in house, and access to full manufacturing data is limited.

1. Raw material extraction:

    - Assess the environmental impacts of extracting materials required for TEGs, such as bismuth telluride (Bi2Te3) and lead telluride (PbTe) (Snyder & Toberer, 2008), and the AC motor itself (copper, aluminium, steel, etc.) (Watari et al. 2021).
    - Consider energy consumption, water usage, and emissions during the extraction process (Huang et al., 2023).

2. Production:

    - Analyse the manufacturing process for TEGs and AC motor components, including energy consumption, waste generation, and emissions (Cutshaw et al., 2023).
    - Evaluate the production process of the aluminium billet for the TEG sandwich plate, considering its energy consumption and waste generation (EPA, 2017). And integrating TEGs into motor casings, particularly those made from aluminium billets machined to follow the motor's curved contour, may increase overall system costs (Jaziri et al., 2020).

3. Use:

    - Assess energy generation from waste heat recovery using the TEG integrated into the AC motor (Massetti et al., 2021).
    - Calculate carbon emissions reduction due to the additional energy generated by the TEG and compare it to the baseline scenario without the TEG.
    - Calculate carbon emissions reduction due to the additional energy generated by the TEG and compare it to the baseline scenario without the TEG

integration (Wang, 2019).

- Consider the overall efficiency of the system and potential maintenance requirements.

4. End-of-life treatment:

- Analyse disposal, recycling, and potential reuse of both the TEG and AC motor components (Goe & Gaustad, 2014).

- Assess the environmental impacts of recycling processes, including energy consumption, waste generation, and emissions (Buchert et al., 2012).

With these reasonable assumptions, the baseline calculation for the LCA translates as follows.

1. Raw material extraction:

Assume that the TEG uses Bi2Te3, which requires 100 g per TEG unit. Raw material extraction for Bi2Te3 consumes around 50 MJ/kg (Snyder & Toberer, 2008). In addition, the AC motor components require 5 kg of copper, 2 kg of aluminium, and 7 kg of steel. The energy consumption for extracting these materials is approximately 60 MJ/kg for copper, 200 MJ/kg for aluminium, and 25 MJ/kg for steel (Huang et al., 2023).

$$Total\ extraction\ energy\ consumption = Material\ mass \times energy\ consumption\ rate \tag{5.4}$$

Table 5.3 – Raw material energy consumption for TEG design

	Mass (kg)	Rate (MJ/kg)	Total energy (MJ)
Bi2Te3	0.1	50	5
Copper	5	60	300
Aluminium	2	200	400
Steel	7	25	175
Total	-	-	**880**

2. Production:

Assume that the production process for TEGs consumes 80 MJ per unit (Cutshaw et al., 2023). The production energy consumption for the AC motor components is approximately 40 MJ for copper, 60 MJ for aluminium, and 20 MJ for steel (EPA, 2017).

Total: 200 MJ

3. Use:

Assuming the TEG generates 3.24 V and 0.0122 A, the power output is 0.0395 W. Over a year (8760 hours), the TEG generates 0.0395 * 8760 = 346 Wh of energy, which translates to 1.25 MJ. Assume that the additional energy generation reduces carbon emissions by 0.5 kg CO2 per kWh generated (Wang, 2019).

$$Carbon\ emissions\ reduction: 346Wh \times 0.5kg\,\frac{CO2}{kWh} = 0.173\ kg\ CO2$$

4. End-of-life treatment:

Assume that 95% of the copper, aluminium, and steel components are recycled, with recycling consuming 20 MJ/kg for copper, 30 MJ/kg for aluminium, and 10 MJ/kg for steel (Buchert et al., 2012).

Table 5.4 – Recycling energy consumption

	Mass (kg)	Rate (MJ/kg)	Recycled quantity (%)	Total energy (MJ)
Copper	5	20	95	95
Aluminium	2	30	95	57
Steel	7	10	95	66.5
Total	-	-	-	**218.5**

Summary of high-level LCA estimations:

Raw material extraction energy consumption: 880 MJ

Production energy consumption: 200 MJ

Energy generation during use: 1.25 MJ

Carbon emissions reduction during use: 0.173 kg CO2

End-of-life recycling energy consumption: 218.5 MJ

It must be noted that these estimations are based on various assumptions and simplifications. A more detailed and accurate LCA would require specific data on the materials, processes, and energy sources involved in each stage of the product life cycle. Furthermore, a complete LCA would also consider other environmental impact categories, such as water consumption, air emissions, and land use.

Implementing some changes from feedback/results in the first run where it was observed that changing stack/motor interface from carbon sheet to heat paste, saw a gain of around 12% in thermal conductivity and around 8% at peak temperature when the fans were implemented using the information from the simulated thermal analysis on the heat sink. Further slight improvements made through machining down the sandwich block to a slightly thinner profile saw an overall 10% reduction to the material used and subsequent mass of the TEG assembly. Knowing the metrics that need to be improved for improvements to the LCA, it is proposed that at least 98% of the metals utilised will be reused by either upcycling or recycling. These small changes thus present scope on which the potential new LCA will be calculated.

The LCA with these improvements is as follows.

1. Raw material extraction energy consumption:

Table 5.5 - Raw material energy consumption for improved TEG design

	Mass (kg)	Rate (MJ/kg)	Total energy (MJ)
Copper	4.5	70	315
Aluminium	1.8	220	396
Steel	6.3	25	157.5
Total	-	-	**868.5**

2. Production energy consumption (10% reduction):

TEG: 72 MJ; Copper: 36 MJ; Aluminium: 54 MJ; Steel: 18 MJ

Total: 180 MJ

3. Use:

Improved TEG power output: 0.0395 W × 1.2 = 0.0474 W

Energy generation during use: 0.0474 × 8760 = 415.344 Wh = 1.495 MJ

Carbon emissions reduction during use: 415.344 Wh × 0.5 kg CO2/kWh = 0.2077 kg CO2

4. End-of-life treatment (98% recycling rate):

Table 5.6 – Recycling energy consumption (improved)

	Mass (kg)	Rate (MJ/kg)	Recycled quantity (%)	Total energy (MJ)
Copper	4.5	20	98	88.2
Aluminium	1.8	30	98	52.92
Steel	6.3	10	98	61.74
Total	-	-	-	**202.86**

Summary of high-level LCA estimations with improvements:

Raw material extraction energy consumption: 868.5 MJ

Production energy consumption: 180 MJ

Energy generation during use: 1.495 MJ

Carbon emissions reduction during use: 0.2077 kg CO_2

End-of-life recycling energy consumption: 202.86 MJ

Comparing the improved LCA with the baseline LCA, the following changes are observed;

Raw material extraction energy consumption: -11.5 MJ (reduced)

Production energy consumption: -20 MJ (reduced)

Energy generation during use: +0.245 MJ (increased)

Carbon emissions reduction during use: +0.0347 kg CO_2 (increased)

End-of-life recycling energy consumption: -15.64 MJ (reduced)

The resulting figures show that these improvements result in a more environmentally friendly system, with reduced energy consumption throughout the life cycle stages and increased energy generation during the use phase.

5.5 DFX Integration – Upcycling and modular Design

This section will discuss the challenges and opportunities associated with the implementation of these concepts in real-world scenarios, ultimately providing valuable insights for designers, manufacturers, and policymakers who wish to promote sustainable practices within their respective fields. By examining the practical applications and implications of upcycling and modular design within the DFX framework, this chapter serves as a cornerstone for exploring the future of sustainable product design and development by analysing the case study results.

5.5.1 Upcycling Case Study Results and discussion:

The case study on upcycling is based on the re-manufacture of old headlights with a modular design that uses affordable and interchangeable parts. The modular design allows for easy replacement of individual components, which reduces the need for complete replacement of the headlight. The data is collected by observing the redesigned headlight performance. In this scenario, due to the fact that these headlights are designed to be used on road going vehicles, the prospect of a survey is rendered redundant – as the statutory and regulatory requirements (DVLA, 2023) will need to be met in order for the proposed new design to be usable. Moreover, the same headlight enclosure has been utilised in this study to further reduce the variables.

Figure 5.15 - Unsuccessful disassembly using the baking process

Figure 5.15 depicts disassembly initially attempted using the baking process (Silva et al., 2021) and is unsuccessful – instead causing damage to the casing and lens. At this point it is established that the headlight is likely sealed using a permaseal type bonding (Silva et al., 2021; Miller et al., 2014; Mingqing et al., 2020).

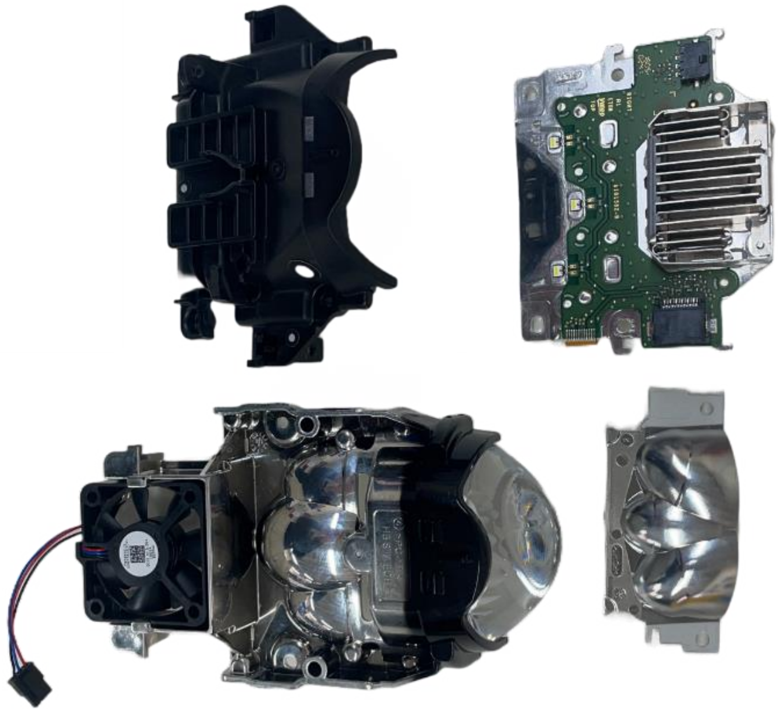

Figure 5.16 - OEM LED subassembly; semi-exploded depiction to allow interrogation/inspection of vital component sub-assembled components

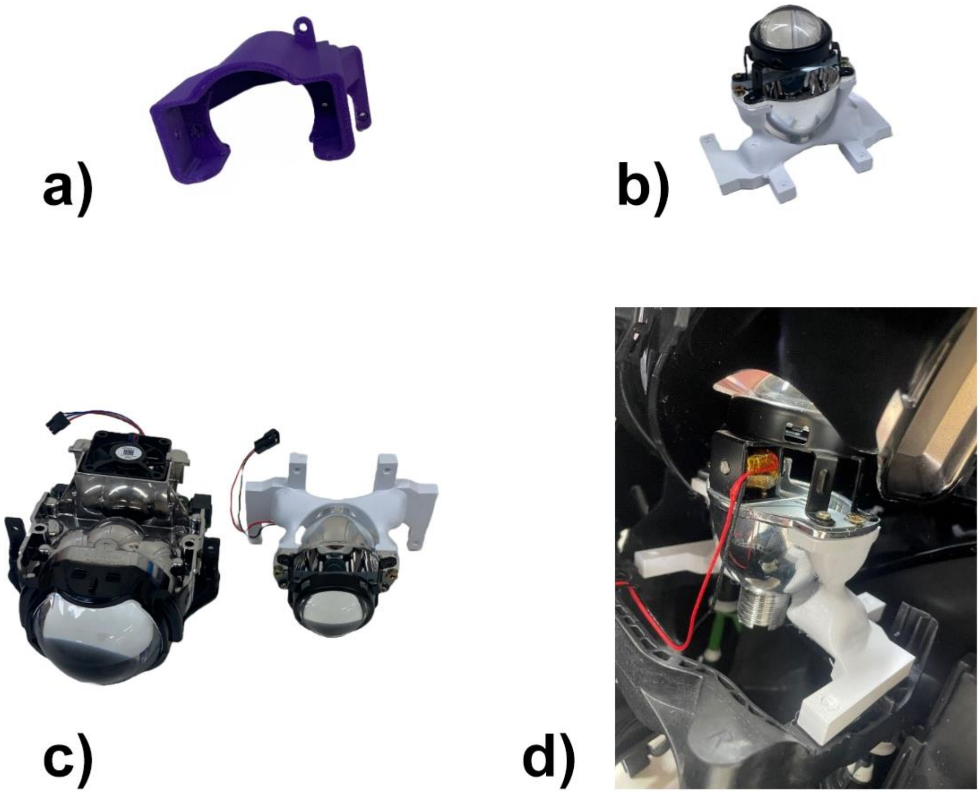

Figure 5.17 - Detailed final assembly and test fit

The images in Figure 5.17 depict the components of the test fit as follows: a) Original bracket examined to set datum for mounting points. b) Light Assembly V2 designed with generative shape design. c) OEM LED assembly vs designed replacement with off-the-shelf parts. d) trial fit assembly of new component - assembly fitment inside the original headlight enclosure.

Figure 5.18 - Final assembly fit test (without cowling)

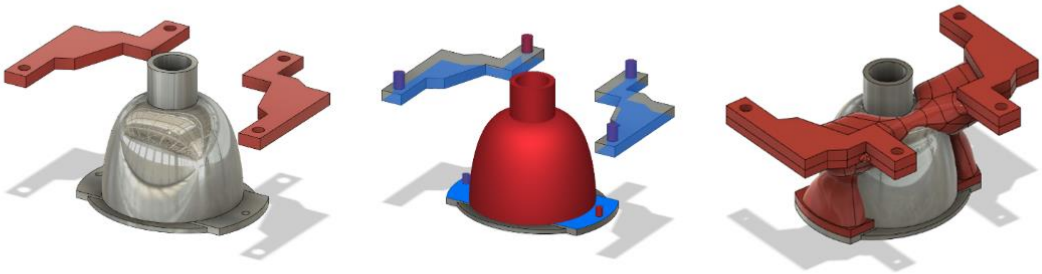

Figure 5.19 - Reaching final design iteration through automated modelling

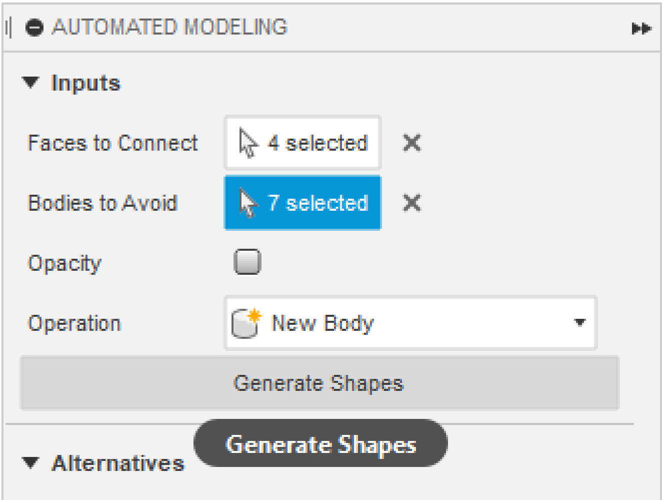

Figure 5.20 - Controls interface during the design iteration process

Figure 5.21 - Completed and reassembled upcycled unit

Figure 5.15 shows the state of the headlight before upcycling consideration. Due to the prevailing challenges in conducting cost-effective repairs, this damaged headlight would have been destined for the scrap yard (Meyer & Beiker, 2014; López-Mosquera et al., 2015; Guo, Ali and Xu, 2023).

Table 5.7 gives an indication of what would be included within a survey – if a different enclosure was to be employed. In this iteration of this study, the table remains unpopulated with specific data as it represents a contingency aspect of the research, specifically addressing the potential evaluation metrics for an alternative enclosure option. The inclusion of this table without data is intended to showcase the comprehensive scope of the study and the consideration given to various scenarios, including the possibility of employing a different enclosure.

The decision not to populate Table 5.7 aligns with the study's current focus on the original enclosure, which was selected due to its unique ability to meet the stringent requirements of the case study. These requirements encompass factors such as; material compatibility, cost-effectiveness, environmental impact and statutory compliance. Finding a replacement enclosure that meets these criteria proved to be a significant challenge, and thus, the study remained centred on the original enclosure.

However, it is crucial to acknowledge that in a different context or with the availability of suitable alternatives, the aspects of 'Appearance', 'Durability', and 'Ease of Repair' would be key factors in assessing the viability of any such alternative enclosure. These factors would be evaluated through a survey, with the results informing the decision-making process.

Table 5.7 - Upcycling survey results

Aspect	**Poor (%)**	**Fair (%)**	**Good (%)**	**Excellent (%)**
Appearance				
Durability				
Ease of Repair				

A key reason to using the original enclosure with this study, is due to the inability to source a replacement enclosure that will fulfil all stringent requirements as detailed below.

In the United Kingdom, the statutory requirements for headlights are specified under the Road Vehicles Lighting Regulations 1989 (RVLR), as amended by the Road Vehicles Lighting (Amendment) Regulations 1994, 1996, 1998, and 2005. Headlights must conform to the requirements set forth in these regulations to ensure road safety and prevent dazzling other road users. The main provisions for headlights include:

1. Position: Headlights must be positioned on the front of the vehicle, with a minimum height of 500mm and a maximum height of 1200mm from the ground. The inner edge of the light must not be closer than 600mm to the longitudinal centreline of the vehicle (Regulation 13).

2. Dipping Mechanism: Headlights must be equipped with a dipping mechanism, allowing the driver to switch between a main beam (full beam) and a dipped beam (low beam). Dipped beams must not cause undue dazzle or discomfort to other road

users and must illuminate the road without shining directly into the eyes of drivers in oncoming vehicles (Regulation 27).

3. Colour: Headlights must emit white or yellow light. Yellow light is permissible only if the vehicle was first used before April 1, 1986 (Regulation 11).

4. Approval Marks: Headlights must bear an approval mark, typically an 'E' mark, to demonstrate that they conform to the relevant European standards (UNECE Regulations) or British standards (BSI Standards). This ensures that the headlights have been tested and certified for safety and performance (Regulation 18).

5. Alignment and Aim: Headlights must be correctly aligned and aimed to ensure proper illumination of the road without causing glare to other road users. This typically involves adjusting the vertical and horizontal aim of the headlights according to the manufacturer's specifications. Periodic checks and adjustments are recommended to maintain optimal performance (Regulation 27).

These regulations stipulate provisions for the position, dipping mechanism, colour, approval marks, and alignment of headlights to ensure road safety and prevent undue dazzle or discomfort to other road users.

Keeping the enclosure as a constant (K) to meet the aforementioned regulations, the intention is to change the internal working mechanism that dictates the light source. This was modified to house a new projector lens, thus allowing flexibility with light source options.

The qualitative results show that the upcycled headlights performed better in luminosity test, due to the integrated design of a changeable LED bulb. This increase in luminosity translates to better road view in real terms, and because the utilised projector has a cut off within, the projected light is within the tolerance limit dictated by the Ministry of Transport, thus conforming to relevant statutory regulations. Figure 5.22 below shows the performance of the original setup with a halogen bulb, followed by the new LED design.

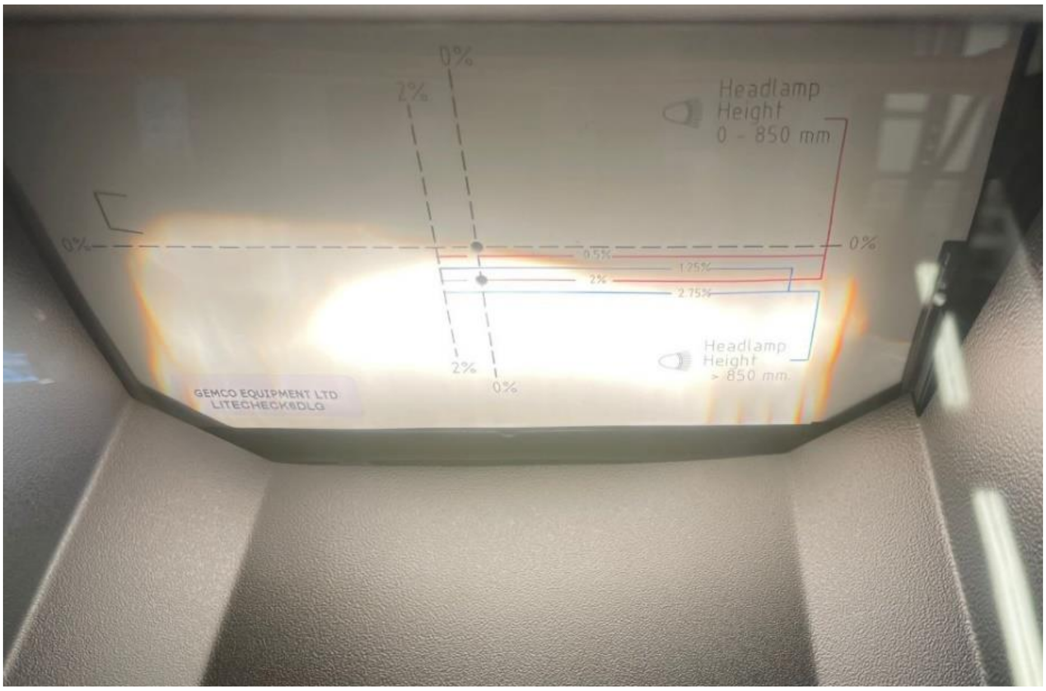

Figure 5.22 - Headlight beam test before upcycling

Figure 5.23 - Headlight luminosity reading before upcycling

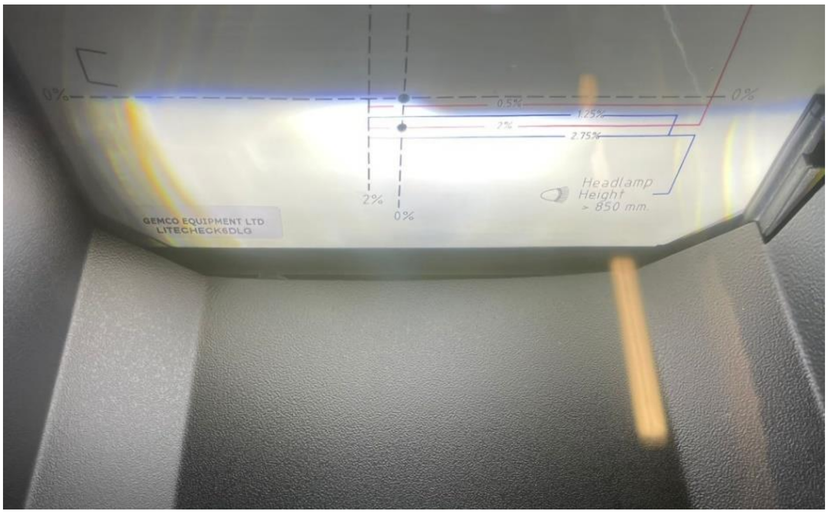

Figure 5.24 - Headlight beam test after redesign

Figure 5.25 - Headlight luminosity reading after redesign

Brighter and more usable light alone is not the only benefit that is observed by this study. To fully validate the positive results, further quantitative analysis is presented and discussed.

To carry out a quantitative analysis of the carbon emissions related to the halogen headlight, a Cradle-to-Grave Life Cycle Assessment (LCA) approach is employed. This comprehensive approach covers the entire life cycle of the product, allowing for the identification of the most significant carbon emissions sources and the implementation of Design for X (DFX) strategies with consideration to upcycling.

Some existing studies have evaluated the environmental impacts of automotive lighting technologies, such as LED and halogen headlights (Rodríguez et al, 2023). Therefore, assumptions and extrapolations based on similar products or industry averages are utilised within this study. Also, due to most of the costing data being presented in US dollars as default, monetary calculations in this research are conducted in US dollar values.

The following assumptions are made for all calculations:

- The lifetime of the halogen headlight is 1,000 hours.
- The power consumption of the halogen headlight is 55 watts.
- The average driving time with headlights on is 500 hours per year.
- The average lifetime of a car is 12 years.

Additional estimates are noted within each calculation, with references for each.

1. Raw material extraction and production:

Assume 5 kg CO2-equivalents per kg of halogen headlight (derived from similar automotive components in literature) (Hischier et al., 2010).

5 kg CO2-eq/kg × 1 kg (assuming 1 kg per headlight)

= 5 kg CO2-eq (Total CO2 emissions for raw material extraction and production)

2. Distribution:

Assume a transportation distance of 10,000 km (average distance from production to end consumer) and 50 g CO2-eq per ton-km (average emissions for road transport) (Ritchie and Roser, 2023).

= 10,000 km × 0.05 kg CO_2-eq/ton-km × 0.001 ton (1 kg headlight)

= 0.5 kg CO_2-eq (Total CO_2 emissions for distribution)

3. Use:

Assume a CO_2 emission factor for electricity generation of 0.5 kg CO_2-eq/kWh (average value for various countries) (Astrup et al., 2009).

55 W × 1,000 hours × 12 years ×0.001 kW/W = 660 kWh total energy consumption during the lifetime of the headlight

660 kWh × 0.5 kg CO_2-eq/kWh

= 330 kg CO_2-eq (total CO_2 emissions for use)

4. End-of-life:

Assume 80% recycling rate for metals and plastics in the headlight, with a CO_2 credit of -1 kg CO_2-eq per kg of recycled material (average value for various recycling processes) (Pan et al., 2011; Schwarz et al., 2021).

-1 kg CO_2-eq/kg × 0.8 kg (80% recycling rate)

= -0.8 kg CO_2-eq (Total CO_2 emissions for end-of-life)

Total CO_2 emissions for the halogen headlight:

5 kg (production) + 0.5 kg (distribution) + 330 kg (use) - 0.8 kg (end-of-life)

= 334.7 kg CO_2-eq

Based on the generic data and assumptions, the total CO_2 emissions for the halogen headlight (baseline calculation) are approximately 334.7 kg CO_2-equivalents over its lifetime. These results will help inform DFX strategies for energy harvesting and upcycling, as well as identify areas for improvement in the production, distribution, use, and end-of-life phases.

Now, making reasonable assumptions and recalculate the new LCA for the redesigned headlight, considering the following changes:

1. Modular parts to allow for repairability.

2. LED bulbs that are changeable/replaceable.

3. Nominal power consumption of 18 watts.

4. Rated for 5 years with more usable light output (Tähkämö et al., 2013).

Assumptions:

- The lifetime of the redesigned headlight is 5 years.
- The average driving time with headlights on is 500 hours per year.
- The average lifetime of a car is 12 years.

1. Raw material extraction and production:

Assume the same CO2 emissions as the original headlight, since the external structure of the headlight enclosure remains the same (Ardente & Mathieux, 2014).

= 5 kg CO2-equivalents

2. Distribution

Assume the same transportation emissions as the original headlight (Kontovas and Psaraftis, 2016; Sarkar et al., 2016).

= 0.5 kg CO2-eq

3. Use:

Total energy consumption during the lifetime of the redesigned headlight:

18 W × 5 years × 500 hours/year × 0.001 kW/W = 45 kWh

45 kWh × 0.5 kg CO_2-eq/kWh (assumed CO_2 emission factor for electricity) (Moomaw et al., 2011)

= 22.5 kg CO_2-eq (total CO_2 emissions for use phase)

4. End-of-life:

Assume the same recycling rate and CO_2 credit as the original headlight (Zackrisson and Hildenbrand, 2022).

= -0.8 kg CO_2-eq

Total CO_2 emissions for the redesigned headlight:

5 kg (production) + 0.5 kg (distribution) + 22.5 kg (use) - 0.8 kg (end-of-life)

= 27.2 kg CO_2-eq

The new LCA for the redesigned headlight shows a significant reduction in carbon emissions compared to the original headlight (27.2 kg CO_2-eq vs. 334.7 kg CO_2-eq). This improvement is primarily due to the reduced power consumption of the LED bulbs (Khan and Abas, 2011) and the extended lifespan (Sudhir, 2016)

Further gains/changes that can be implemented to make the redesigned headlight even greener include:

1. Improving the energy efficiency of the LED bulbs, which would further reduce power consumption and carbon emissions during use (Khan and Abas, 2011).

2. Utilising recycled materials for the production of the headlight components, which could lower the carbon emissions associated with raw material extraction and production (Ardente & Mathieux, 2014).

3. Implementing more sustainable production processes with reduced energy consumption and lower carbon emissions (Cai et al., 2019).

4. Encouraging consumers to recycle the headlight components at the end-of-life to

further increase recycling rates and reduce landfill waste (Zackrisson and Hildenbrand, 2022).

5. Optimizing the transportation and distribution process to reduce the carbon emissions associated with shipping the headlight components (Cai et al., 2019).

Furthermore, a comprehensive cost-benefit analysis (CBA) for the redesigned headlight will also be carried out, involving comparing the costs and benefits associated with the original halogen headlight and the new, more energy-efficient and environmentally friendly design. For this analysis, the focus is on the following four aspects: production costs, energy costs, environmental costs, and maintenance costs.

1. Production costs: Assuming the redesigned headlight uses modular components, the production costs might increase slightly due to the additional complexity in manufacturing (Mishra, 2016). However, by using recycled materials and improving production processes, it's possible to offset this cost increase (Ardente and Mathieux, 2014).

2. Energy costs: As calculated earlier, the redesigned headlight consumes significantly less energy than the original halogen headlight (45 kWh vs. 250 kWh over a 5-year lifetime). This results in cost savings for the user. Assuming an average electricity cost of \$0.12/kWh (An et al., 2020), the energy cost savings are:

$$(250\ kWh - 45kWh) \times \$0.12 = \$24.60$$

3. Environmental costs: The redesigned headlight has a lower carbon footprint, which results in reduced environmental costs. Assigning a monetary value to the reduction in carbon emissions is challenging, but one approach is to use the social cost of carbon (SCC). The SCC is an estimate of the economic damages associated with a small increase in CO_2 emissions (Van Den Bergh and Botzen, 2015). In 2021, the EPA estimated the SCC to be \$51 per metric ton of CO_2 (\$0.051 per kg). Using this value, the environmental cost savings can be calculated as:

$$(334.7\ kg\ CO2eq - 27.2\ kg\ CO2eq) \times \$0.051 \approx \$15.68$$

4. Maintenance costs: The redesigned headlight's modular design and replaceable LED bulbs result in lower maintenance costs. While it is difficult to estimate the exact maintenance cost savings without specific data, one can assume that these savings will be substantial, as LED bulbs generally have a longer lifespan and lower failure rates than halogen bulbs (Tähkämö et al., 2013).

Outcome after 5 years: Assuming a 5-year lifetime for the redesigned headlight, the quantitative analysis indicates the following cost savings:

- Energy cost savings: $24.60
- Environmental cost savings: $15.66

Additionally, one can expect significant maintenance cost savings due to the longer lifespan and lower failure rates of LED bulbs (Tähkämö et al., 2013). While it is challenging to provide an exact figure without specific data, the overall benefits, including lower energy costs, reduced environmental costs, and decreased maintenance costs, outweigh the potential increase in production expenses.

Implementing the redesigned headlight will likely lead to significant long-term cost savings and reduced environmental impact after 5 years.

5.6 Summary

In this chapter, the exploration of various energy harvesting techniques for carbon reduction within manufacturing was undertaken, focusing on three primary avenues: radio frequency (RF) harvesting, thermoelectric generator (TEG) integration, and upcycling through Design for X (DFX) principles. The results obtained were not uniform in their promise, with each approach presenting its own set of challenges and opportunities for improvement. The ultimate aim of this research is to contribute significantly to carbon reduction in manufacturing, and the findings indicate that some methods hold greater potential than others.

The investigation into RF harvesting faced considerable limitations, primarily due to the limitations of the university's equipment and facilities for producing antennas in-house. This bottleneck in research led to a focus on TEG integration, with the assumption that a more efficient RF harvester would be coupled with the TEG system in the future. Despite the initial promise of TEG integration, a comprehensive cost-benefit analysis (CBA) revealed a lengthy return on investment (ROI) period, casting doubt on the economic viability of this approach.

By employing aggressive cost-saving strategies and conducting further research into identifying a richer energy harvesting frequency, the development of an optimised RF harvesting antenna could render the RF and TEG integration methods more economically feasible, thereby reducing the ROI time significantly. While these areas require additional research and development, they present opportunities for future advancements in carbon reduction within manufacturing.

The most striking success of this research, however, emerged from the integration of upcycling through DFX principles. The headlight case study showcased exceptional gains in both the life-cycle assessment (LCA) and the CBA analysis, highlighting the significant potential of this approach in achieving the overall goal of carbon reduction in manufacturing. It is worth noting that the current analysis only considered a portion (the internal working mechanism) of the headlight, suggesting that even more significant improvements could be achieved when the entire enclosure is incorporated into the integrated DFX upcycling process.

The critical role of industry knowledge in interpreting these results cannot be overstated. The positive outcomes obtained from the headlight case study demonstrate the potential for future improvements in carbon reduction within manufacturing. The expertise of industry professionals contributes to a more comprehensive understanding of the practical implications of the findings, which in turn informed the direction of the research.

In conclusion, this chapter explored the viability of various energy harvesting techniques for carbon reduction within manufacturing, with the results indicating that upcycling through DFX principles holds the most promise for significant gains in carbon reduction.

The RF harvesting and TEG integration approaches faced challenges, but also offered opportunities for future improvements. By addressing these challenges and capitalising on the potential for optimisation, it is possible that these techniques could contribute to the overall goal of carbon reduction in manufacturing as well.

The key takeaway from this research is that while some energy harvesting techniques may not currently be as economically viable as others, they still offer valuable avenues for future investigation and development. The successful integration of upcycling using DFX principles, as demonstrated in the headlight case study, underscores the importance of industry knowledge in driving innovation and achieving meaningful results in carbon reduction within manufacturing. It is through the continued pursuit of these research avenues and the willingness to learn from industry experts that we can hope to make substantial progress in reducing the carbon footprint of manufacturing processes.

5.7 Best practice recommendations

The results of the literature review and experimental work conducted provide evidence to support the recommendations for best practices in batch manufacturing detailed below. This will also form the basis of future work.

Based on the findings of this thesis, the following best practice recommendations can be derived to facilitate the implementation of DFX principles towards net-zero emissions in manufacturing:

1. Design for upcycling: Manufacturers should design components with upcycling in mind from the start, ensuring easy disassembly, reconfiguration, and reuse (Bocken et al., 2016; Linder et al., 2017). This can be achieved through modular designs and material selection that enable efficient repurposing and recycling (Geissdoerfer et al., 2020). The headlight case study presented in this thesis demonstrated exceptional overall gains in both the LCA study and CBA analysis when DFX principles were integrated.

2. Optimise energy harvesting systems: Enhance ambient RF energy harvesting systems to minimise losses and improve efficiency (Olgun et al., 2011). This can be achieved through advances in technology, innovative methods for capturing energy, and integration with other renewable energy sources (Patterson, Singh and Cho, 2022). The difficulty/limitation during the RF exploratory test highlighted the need for better equipment and facilities to produce antennas in-house (in this case), as well as the importance of identifying richer energy harvesting frequencies for improved RF research.

3. Improve thermoelectric generators (TEGs): Invest in research and development to optimise TEGs, enhance efficiency, and develop more efficient thermoelectric materials (Yang et al., 2017; He et al., 2017). This will contribute to cleaner and more sustainable manufacturing practices by harnessing waste heat from electric motors (Zeb et al., 2017). This is evident in the TEG experiment carried out for the work within this thesis, which initially showed promising results from TEG integration, but further comprehensive CBA revealed a lengthy ROI. With the conclusion being drawn being that an aggressive cost-saving strategy, combined with optimised RF harvesting antennas, could improve the financial viability and reduce the ROI time.

4. Foster collaboration and knowledge sharing: Encourage partnerships between manufacturers, research institutions, and technology providers to drive innovation in sustainable manufacturing practices (Muhuri et al, 2019); Sarkis et al., 2020). This will facilitate the adoption of DFX principles and promote the development of new technologies and processes. The work with all the case studies carried out emphasised the role of cooperation in adopting DFX principles and advancing new technologies and processes. Industry knowledge was vital in understanding the results and identifying potential future improvements – thanks to a combination of prior industry experience by both the researcher and the supervisory team.

5. Integrate DFX principles into policymaking and standardisation: Engage with policymakers and standardisation bodies to incorporate DFX principles into

regulations and guidelines that promote sustainable manufacturing practices and facilitate the achievement of net-zero emissions (Ghisellini et al., 2016; Damiani et al., 2015). The headlight case study's success in reducing carbon emissions serve as an example for policymakers to consider when developing regulations and guidelines.

6. Develop targeted education and training programs: Raise awareness and build capacity among industry professionals by offering courses and workshops focused on implementing DFX principles and other sustainable manufacturing practices (Ferrer-Estévez and Chalmeta, 2021; Erol et al., 2016). The experience presented within the headlight case study highlights the importance of industry knowledge in understanding and interpreting results, emphasising the need for continued education and training.

7. Leverage digital technologies: Incorporate Industry 4.0 technologies, such as IoT, AI, and big data analytics, to support energy-efficient production, optimised resource management, and improved process control (Ghobakhloo, 2020; Liao et al., 2017). This will aid in the transition towards net-zero emissions in the manufacturing sector. The use of these technologies could help researchers and manufacturers identify richer energy harvesting frequencies and develop optimised RF harvesting antennas, as identified within this thesis where the non-availability of a PCB mill within the testing facilities (and lengthy lead times for subcontracting designed builds of patch antennas) limited the scope of exploring other potentially available energy rich bandwidths.

8. Address social and economic aspects: Consider the barriers to adoption, such as financial constraints, lack of skilled workforce, and resistance to change (Bocken et al., 2014; Shojaei and Burgess, 2022). Develop strategies to overcome these challenges and assess the impact of DFX principles on job creation and regional development (Gohoungodji et al., 2020; Galgóczi, 2012). The work within this thesis demonstrates that aggressive cost-saving strategies and further research on energy harvesting could help make TEG integration more economically viable and reduce

ROI time.

9. Implement sustainable business models: Develop business models that capture the value generated through DFX practices and incentivize manufacturers to embrace these principles (Lüdeke-Freund et al., 2019; Ünal, Urbinati and Chiaroni, 2019). This includes integrating circular economy principles, waste reduction, resource optimisation, and product life extension (Geissdoerfer et al., 2017; Kalmykova et al., 2018). The headlight case study in this thesis serves as a model for how a sustainable business approach can yield significant environmental and economic benefits. In this case, one could easily make the assumption that if the auto manufacturer implemented some of the suggested practices, they would still be the ones to market the spare parts required to maintain/repair the headlight.

10. Promote industry-academia collaboration: Encourage partnerships between industry and academia to foster innovation and knowledge exchange (Ranta et al., 2018; Tukker et al., 2020). This will help advance sustainable manufacturing practices and support the development of new technologies. Within the observations of this thesis, such collaboration would have potentially addressed the limitations in equipment and facilities for producing antennas in-house, while also promoting further research on TEG integration and RF energy harvesting.

By implementing these best practice recommendations, manufacturers with little or no existing ‘green’ strategies can begin to effectively implement sustainable manufacturing processes, ultimately moving closer to achieving net-zero emissions.

6. CONCLUSIONS AND FUTURE WORK

6.1 The Connection

In line with the aim and objectives of this research, this section clarifies the significance of the links between the different elements of this work, and specifically show how they come together towards achieving the set aim and objectives. The link between RF & TEG setups, DFX principles, upcycling, and batch production can be understood by examining their collective contributions to the overarching goal of sustainable manufacturing and reduced environmental impact.

Radiofrequency (RF) energy harvesting captures ambient RF energy, such as that emitted by Wi-Fi routers, to generate electricity (Olgun et al., 2011). Thermoelectric generators (TEGs) convert waste heat from manufacturing processes, like electric motors, into electricity (Yang et al., 2017). Both RF and TEG setups support energy efficiency and reduce reliance on non-renewable energy sources, contributing to the goal of net-zero emissions in manufacturing.

DFX principles aim to optimise product design and manufacturing processes by considering various factors, such as manufacturability, assembly, sustainability, and upcycling (Bocken et al., 2016). Implementing DFX principles can lead to reduced material waste, improved energy efficiency, and increased product longevity, supporting the transition to more sustainable manufacturing practices.

Upcycling is the process of transforming waste materials or end-of-life products into new materials or products with higher quality or value (Galgóczi, 2012). By incorporating upcycling practices into product design and manufacturing processes, manufacturers can reduce waste, conserve resources, and minimise the environmental impact of production. Furthermore, it could also be said that the ambient RF and waste heat being harvested for generation of energy are actually being upcycled.

Batch production is a manufacturing method in which products are produced in finite quantities or "batches" before moving on to the next product variant or model (Xia et al., 2015). This approach allows for greater flexibility in manufacturing processes and can facilitate the implementation of DFX principles, such as modular design and upcycling. By incorporating DFX principles and upcycling, batch production can contribute to reduced waste, minimised resource consumption, and decreased carbon emissions (Ghisellini et al., 2016).

Holistically, the link between all the elements within this research is that they all contribute to the overarching goal of sustainable manufacturing and reducing environmental impact. RF and TEG setups enhance energy efficiency, while DFX principles help optimise product design and manufacturing processes. Upcycling, as an element of the DFX principles, aids in reducing waste and conserving resources, and batch production allows for greater flexibility in implementing these principles. The effective integration of these elements can lead to a more energy-efficient, environmentally responsible, and resource-conscious manufacturing process, which supports the transition towards net-zero emissions in the manufacturing sector.

6.2 Conclusion

In summary, this thesis aimed to investigate the application of Design for Excellence (DFX) principles in achieving net-zero emissions within the manufacturing sector. A multi-faceted approach was taken, encompassing energy harvesting from manufacturing environments, ambient radiofrequency (RF) energy harvesting, thermoelectric generators (TEGs) integrated with electric motors, and the incorporation of upcycling practices in the initial design of components.

The case studies conducted provided valuable insights into the potential of these techniques in contributing to sustainable manufacturing. Upcycling emerged as a promising option for reducing carbon emissions, particularly when components are designed with upcycling in mind from the start. However, the research revealed the need for further improvements at the point of manufacture, such as implementing modular designs to facilitate easier disassembly and reassembly of products.

RF energy harvesting demonstrated the capacity to consistently capture ambient energy, but its efficiency in generating useful energy was constrained by conversion losses. This limitation highlights the need for ongoing research and development to improve the overall efficiency of RF energy harvesting systems, making them more viable for widespread adoption in the manufacturing industry.

Thermoelectric generators (TEGs) mated to electric motors showcased a strong performance across the board, indicating their potential as a viable energy recovery solution. However, the research identified the need for further optimisation of TEG technologies, which could enhance their effectiveness in reducing energy consumption and contributing to net-zero emissions.

In light of these findings, it is evident that the successful implementation of DFX principles, energy harvesting techniques, and upcycling practices could play a crucial role in the transition to sustainable manufacturing. By integrating these approaches, manufacturers can reduce their environmental impact, lower carbon emissions, and improve energy efficiency. This research contributes to a growing body of knowledge on sustainable manufacturing practices, highlighting the potential of innovative techniques to support the global transition towards net-zero emissions. Nevertheless, it is important to acknowledge that the journey towards sustainable manufacturing is complex and multifaceted. While this thesis provides valuable insights, several challenges and limitations must be considered.

In conclusion, this research provides a foundation for understanding the potential of DFX principles, energy harvesting technologies, and upcycling practices in promoting sustainable manufacturing. The case studies demonstrated the viability of these approaches, but also highlighted areas where further research and optimisation are needed. By acknowledging the limitations of this study and building upon its findings, future research can continue to advance the knowledge and application of sustainable manufacturing practices, ultimately contributing to the global goal of achieving net-zero emissions.

6.3 Research limitations

While this thesis provides valuable insights into the application of DFX principles for sustainable manufacturing, a few limitations noticed through this research that must be acknowledged are listed below:

1. Limited case studies: The findings of this research were based on a selected number of case studies due to available resources (especially within RF) and scope of investigative cost, even though these give a broad indication of what is attainable, it may not be representative of the broader manufacturing industry. Future research could expand the scope by including a larger and more diverse range of case studies.

2. Complex Economic considerations: This thesis focused on the environmental benefits of DFX principles, energy harvesting, and upcycling practices. It also explores the cost-benefit analysis. Further research could explore the more complex economic implications of these techniques, such as the Return on Investment (ROI) for manufacturers and policy makers alike.

3. Implementation barriers: The research did not delve deeply into the potential barriers to implementing DFX principles, energy harvesting technologies, and upcycling practices in manufacturing. Future studies could investigate the challenges and barriers faced by manufacturers and propose strategies to overcome these obstacles.

4. Technological advancements: As the field of sustainable manufacturing is constantly evolving, new technologies and approaches may emerge, potentially changing the landscape of energy harvesting and upcycling practices. This thesis may not fully capture such advancements due to the rapidly changing nature of the field.

In conclusion, this thesis contributes to the understanding of how DFX principles can support the transition towards net-zero emissions in manufacturing by exploring energy harvesting techniques and upcycling practices. The case studies revealed the potential of these approaches in reducing carbon emissions and improving energy efficiency, but also highlighted areas where further research and optimisation are needed. Acknowledging the limitations of this study can inform future research directions and provide a more comprehensive understanding of sustainable manufacturing practices.

6.4 Future Work

The underlying theory behind energy harvesting from the ambient (in this case RF and waste heat from industrial machinery) look favourable. For future research and development efforts in the context of this thesis, the following areas warrant further exploration and advancement to promote the implementation of DFX principles and support the transition towards net-zero emissions in manufacturing:

1. Social and economic impact analyses: Investigate the broader implications of implementing DFX principles and energy harvesting technologies on job creation, skill development, and regional growth, providing a more comprehensive understanding of the potential benefits and challenges.

2. Policy implications and recommendations: Examine the influence of governmental policies, incentives, and regulations on the adoption of DFX principles and energy harvesting technologies. Provide well-informed recommendations for policy adjustments that encourage sustainable manufacturing practices.

3. Cross-sectoral and international collaboration: Explore opportunities for cross-sectoral and international partnerships to accelerate the adoption of DFX principles and energy harvesting technologies, fostering knowledge exchange and the sharing of best practices and lessons learned.

By concentrating on these future research and development recommendations, researchers and industry practitioners can contribute significantly to the ongoing advancement of sustainable manufacturing practices and facilitate the transition towards net-zero emissions in the manufacturing sector.

6.5 *Publications*

Journals

- Ukala, A. & Ukala, Chinyere & Thomas, Martin & Ogbodo, Eugene. (2023). Engaging Young Minds: A Novel Approach to E-Learning in STEM Subjects. European Modern Studies Journal. 7. 213-217. 10.59573/emsj.7(4).2023.19

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- A. N. Ukala, M. Thomas and E. A. Ogbodo "Towards Net Zero — A Hybrid Energy Harvesting System for Sustainable Wireless Sensor Networks in Industrial Applications (Part 2 Fabricate & Test), "IEEE, April 2024(*Under review*).

Conferences

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- Azunka Ukala, Mithun Mohan, Eugene Ogbodo and Abu Zafar Md. Imran: "A Novel Single-Band Antenna for Enhanced V2X Communication: Review

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- Azunka Ukala, Sayed Ahmad and Eugene A. Ogbodo: "Enhanced Dual-Band Antenna for Intelligent Vehicular and Infrastructure Communications "IEEE, April 2024 (*Accepted in-press*).

- Azunka Ukala, Hassan Sarfraz, Eugene A. Ogbodo and Eze Stella Ifeyinwa: "Advanced Filtering Power Dividers: Achieving Superior Isolation in RF Applications "IEEE, April 2024 (*Accepted in-press*).

- Azunka Ukala, Abu Zafar Md. Imran, Eugene A. Ogbodo and Martin Thomas: "ITS-G5 Antennas: Powering Future Urban Transports "IEEE, April 2024 (*Accepted in-press*).

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8. APPENDICES

APPENDIX A: Technical & Performance details for mini-Dipole (antenna benchmarking base point)

2.4GHz Antenna

Mini Dipole

Features

- $^1/_4$ Wavelength Dipole Antenna
- Rugged Flexible Plastic Finish.
- SMA-Male or F type Male Fixing.
- Omni-Directional Design
- 50ohm Impedance
- Operating Temp –30 to +60°C
- Insulation resistance 500MΩ @500Vdc

Applications

- General Low Power Radio
- M2M Applications
- Telemetry

Description

A compact PCB Antenna for 2.4GHz applications where high performance is required from a small size. Using the ANT-24G-DPL antennas will give optimum range and reliability to your application.

Ordering Information

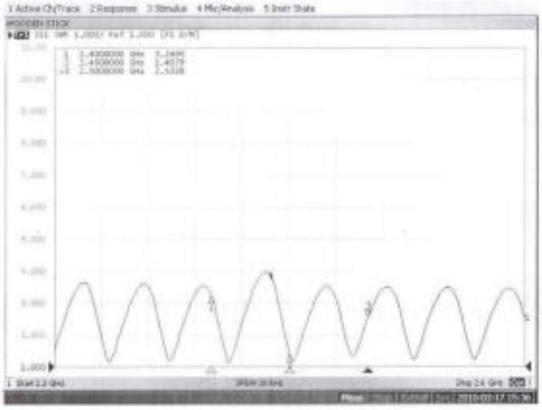
PART No	Description
ANT-24G-DPL-FP	MINI DIPOLE Antenna, 2.4-2.5GHZ, 2.1DBI GAIN, 2.5M CABLE F(M) type connector
ANT-24G-DPL-SMA	MINI DIPOLE Antenna, 2.4-2.5GHZ, 2.1DBI GAIN, 2.5M CABLE SMA(M) connector

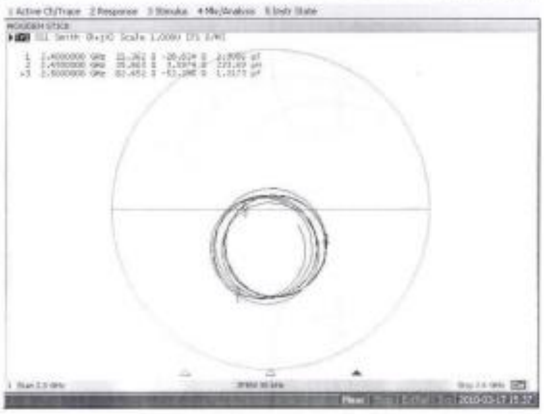
FM76316

DS ANT-24G-DPL-3

www.rfsolutions.co.uk

Performance / VSWR Plot

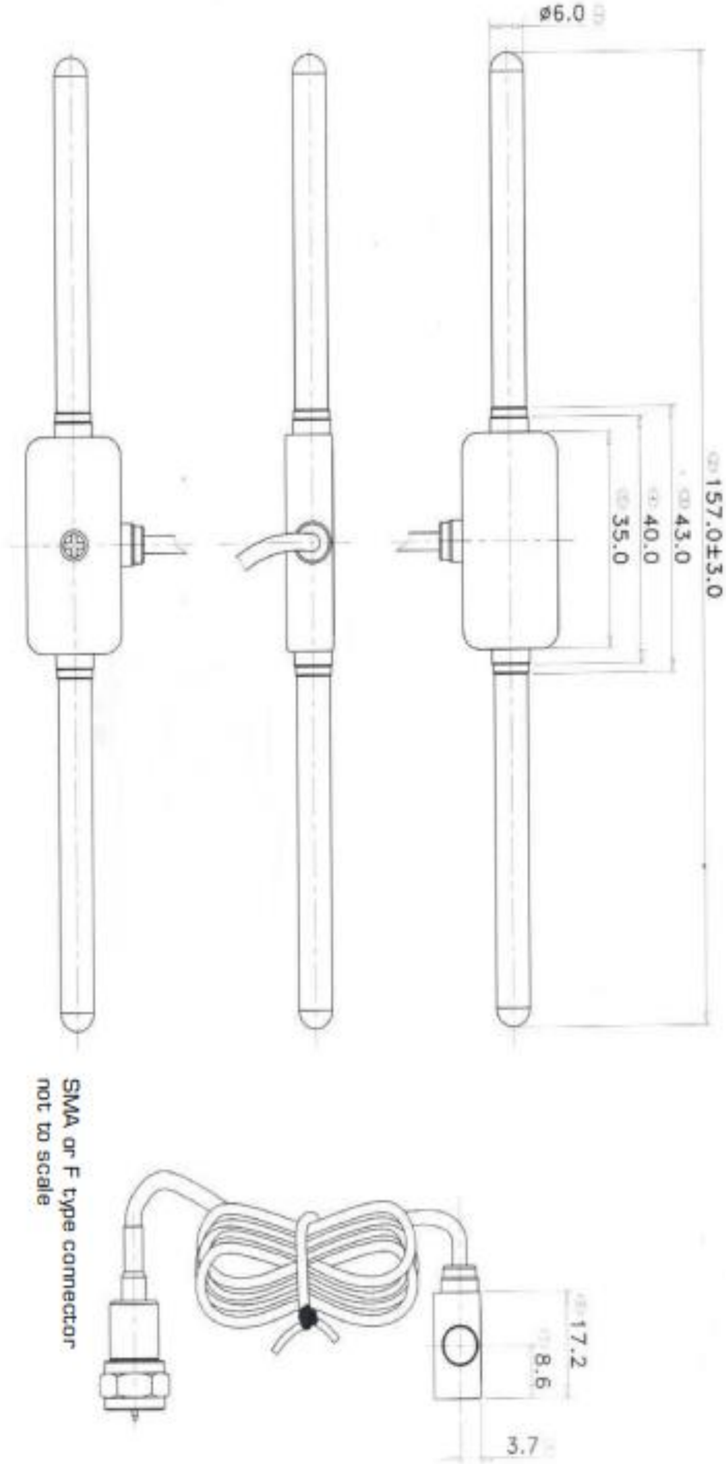




RF Solutions Ltd. Recycling Notice
Meets the following EC Directives:
DO NOT
Discard with normal waste, please recycle.
ROHS Directive 2011/65/EU and amendment 2015/863/EU
Specifies certain limits for hazardous substances.
WEEE Directive 2012/19/EU
Waste electrical & electronic equipment. This product must be disposed of through a licensed WEEE collection point. RF Solutions Ltd., fulfils its WEEE obligations by membership of an approved compliance scheme. Environment Agency Producer Registration Number: **WEE/JB0104WV.**

Waste Batteries and Accumulators Directive 2006/66/EC
Where batteries are fitted, before recycling the product, the batteries must be removed and disposed of at a licensed collection point.

Mechanical Dimensions



APPENDIX B : Technical details for energy harvester and battery charger – boost configuration (Energy storage option)

STEVAL-ISV019V1

Evaluation board for SPV1050 ULP energy harvester and battery charger – boost configuration

Data brief

Features

- First startup at Vin = 500 mV
- Input voltage working range: 150 mV ≤ Vin ≤ V_{EOC}
- End of charge battery voltage: V_{EOC} = 4.25 V
- Battery undervoltage protection: V_{UVP} = 3.7 V

Applications

- Charge any battery chemistry, including lithium based, NiMH, solid state thin film and supercapacitor.
- WSN, HVAC, building and home automation, industrial control, access control, smart lighting, asset and livestock positioning and tracking, surveillance.
- Body area network, sportswear, fitness.

Description

The STEVAL-ISV019V1 is an evaluation board based on the ultralow power energy harvester and battery charger SPV1050. For any detail related to the SPV1050 features and performances please refer to the datasheet.

The evaluation board implements the boost configuration of the DC-DC converter and has the purpose of enhancing the SPV1050 based applications development by testing the silicon performance thanks to many jumpers and test points, and by helping to find out the best system configuration to make the SPV1050 device working at the most of efficiency.

The STEVAL-ISV019V1 is optimized to:

Harvest energy from PV panels supplying 0.5 V ≤ V_{MP} ≤ 2.5 V and 30 µA ≤ I_{MP} ≤ 20 mA.

Charge a battery with 3.7 V undervoltage protection threshold (V_{UVP}) and 4.2 V end of charge voltage threshold (V_{EOC}).

Nevertheless, few easy changes on the application components (input and output resistor partitioning, C_{IN} capacitor) allow to use a different PV panel and source (like TEG), and a battery by setting the V_{MPP_SET}, the V_{UVP} and the V_{EOC} thresholds according to the new source and load. More in detail, operating ranges can be extended as follows: V_{MP} from 150 mV up to 5 V, I_{MP} up to 100 mA, V_{UVP} down to 2.2 V and V_{EOC} up to 5.3 V.

1 Schematic and bill of material

The schematic, bill of material and gerber files can be downloaded from the Design resources tab of the STEVAL-ISV019V1 product folder on www.st.com.

Figure 1. Schematic

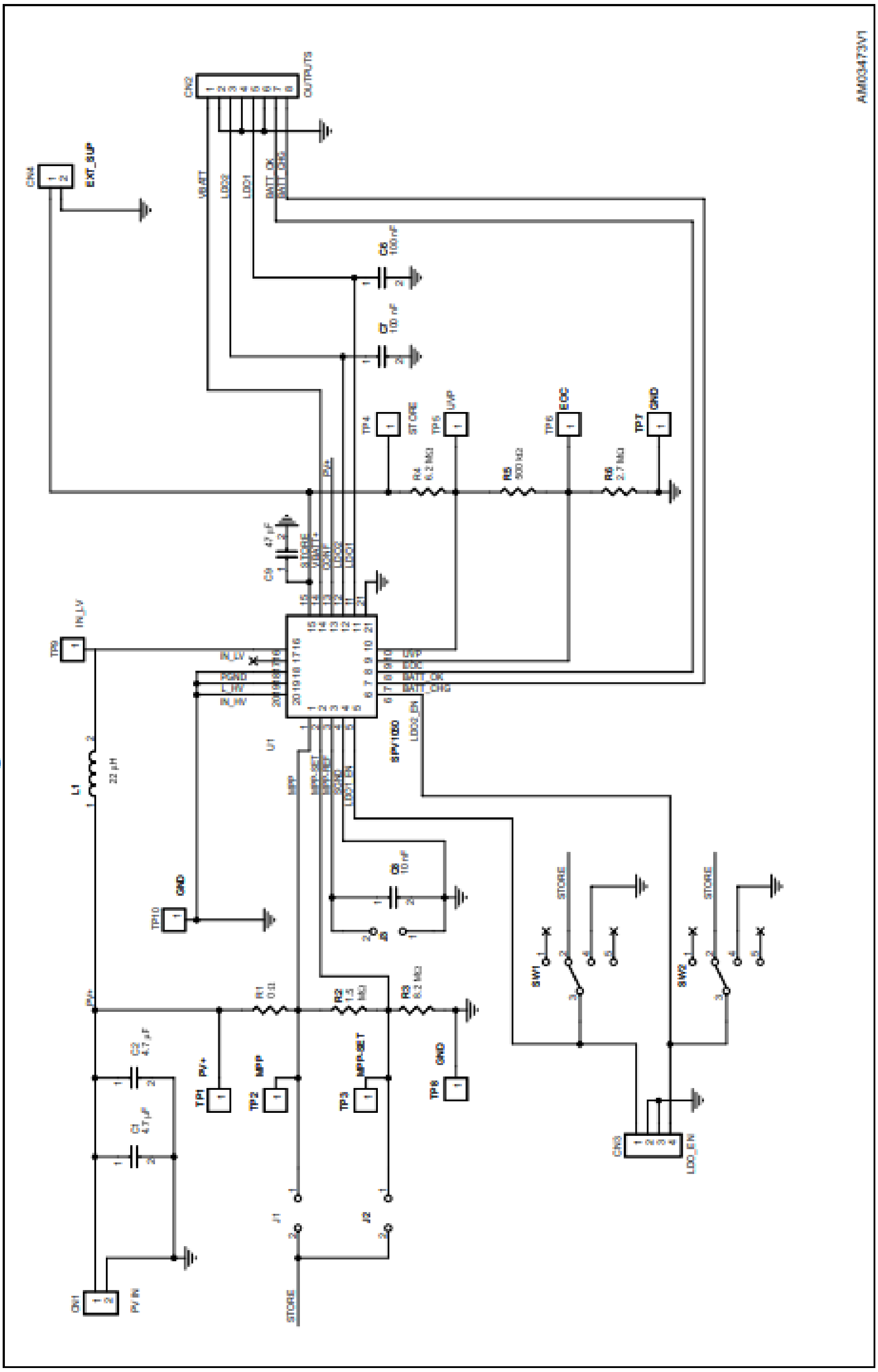


Table 1. Bill of material

Sect.	Item	Q.ty	Reference	Part / value	Toler. %	Voltage current	Watt	Technol. info.	Package	Manufacturer	Manufacturer code	More information
DC-DC input section	1	1	U1	SPV1050					VFQFPN 3 x 3 x 1 20L (code A0BR)	ST	SPV1050	
	2	1	CN1	2-ways screw connector						TE Connectivity	282834-2	Input connector for PV panel or TEG
	3	1	C1	4.7 µF	15%	16 V			0805	Murata	GCM21BR71C475KA73L	Input capacitance
	4	0	C2 (DNM)	4.7 µF	15%	16 V			0805	Murata	GCM21BR71C475KA73L	
	5	3	J1, J2, J3	jumper				Pitch 2.54 mm	TH			Enable/disable MPPT
	8	1	R1	0 Ω	1%				0805	VISHAY	CRCW08052M70FKEA	Resistor partitioning for MPP track/setting
	9	1	R2	1.5 MΩ	1%				0805	VISHAY	CRCW08051M50FKEA	
	10	1	R3	8.2 MΩ	1%				0805	YAGEO	232273468205	
	11	1	L1	22 µH	20%					Coilcraft	LPS4018-223ML_	DC-DC inductor
	12	1	C8	10 nF	15%	16 V		X7R	0603	Murata	GRM188R71C103KA01D	Voltage sampling time constant capacitance

Table 1. Bill of material (continued)

Sect.	Item	Q.ty	Reference	Part / value	Toler. %	Voltage current	Watt	Technol. info.	Package	Manufacturer	Manufacturer code	More information
Battery section	13	1	CN4	2-way screw connector						TE Connectivity	282834-2	Connector for external supply of pin STORE
	14	1	C9	47 µF	20%	10 V			0805	TDK	C2012X5R1A476M125AC	
	15	1	R4	6.2 MΩ	5%				0805	RS	RS-0805-6m2-5%-0.125W	Resistor partitioning for UVP, EOC, protection setting
	16	1	R5	499 kΩ	1%				0805	VISHAY	CRCW0805499KFKEA	
	17	1	R6	2.7 MΩ	1%				0805	VISHAY	CRCW08052M70FKEA	
	18	1	CN2	8-way screw connector						TE Connectivity	282836-8	Connector for battery and battery status signals
LDOs section	19	2	C6, C7	100 nF	10%			X7R	0603	KEMET	C0603C104K4RAC	Tank capacitor for LDOs
	21	2	SW1, SW2	5-pin male Stripline				Pitch 2.54 mm	TH			Close 2 - 3: LDO disabled Close 1 - 2: LDO enabled Floating: external control through CN3
	23	1	CN3	4-way screw connector						TE Connectivity	282836-4	Connector for LDOs enable connection

Table 1. Bill of material (continued)

Sect.	Item	Q.ty	Reference	Part / value	Toler. %	Voltage current	Watt	Technol. info.	Package	Manufacturer	Manufacturer code	More information
List of test points	25	1	TP1					True hole				PV+ pin sensing and soldering
	26	1	TP2					True hole				MPP pin sensing and soldering
	27	1	TP3					True hole				MPP-SET pin sensing and soldering
	28	1	TP4					True hole				STORE pin sensing and soldering
	29	1	TP5					True hole				ULP pin sensing and soldering
	30	1	TP6					True hole				EOC pin sensing and soldering
	31	1	TP7					True hole				GND pin sensing and soldering
	32	1	TP8					True hole				GND pin sensing and soldering
	33	1	TP9					True hole				IN_LV pin sense (for probe scope)
	34	1	TP10					True hole				GND pin sensing (for probe scope)

2 Layout

From *Figure 2* to *Figure 4* show the component placement and the layout (top and bottom views) of the STEVAL-ISV019V1.

Figure 2. Layout - silkscreen view

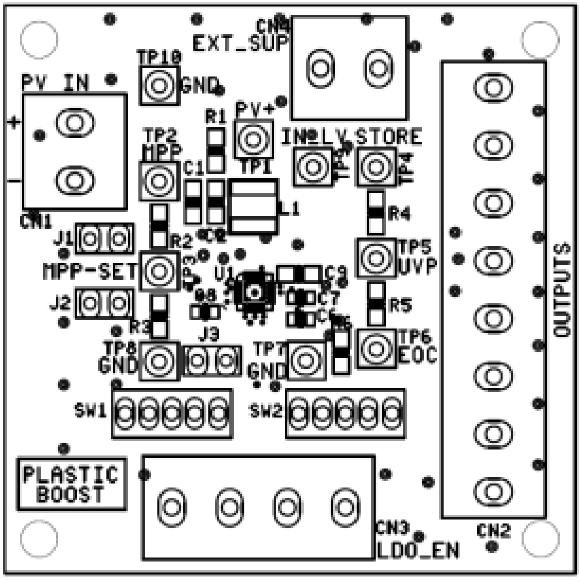


Figure 3. Layout - top view

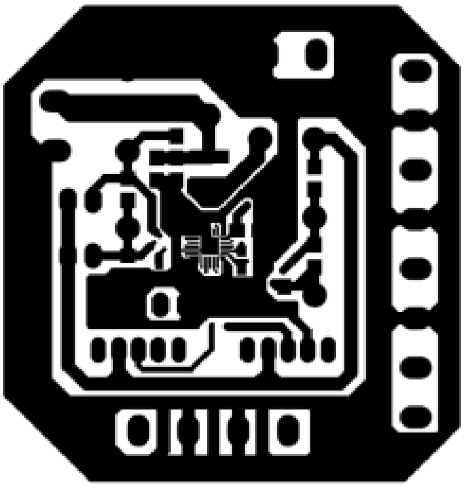
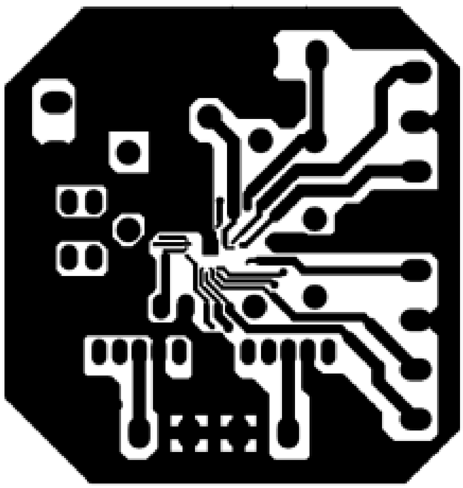


Figure 4. Layout - bottom view



3 Revision history

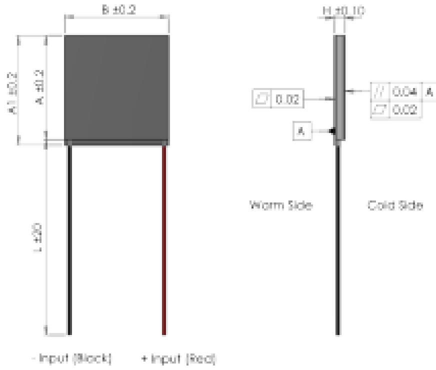
Table 2. Document revision history

Date	Revision	Changes
27-Nov-2013	1	Initial release.
29-Apr-2014	2	Updated *Section : Features on page 1* (updated values of "First startup at Vin" and "Input voltage working range"). Updated *Section : Description on page 1* (updated values of "Harvest energy from PV panels supplying", added extended operating ranges). Updated *Section 1: Schematic and bill of material on page 2* (updated web link). Updated *Figure 1: Schematic on page 3* (updated value of C9 capacitor, minor modifications). Updated *Table 1: Bill of material on page 4* (removed "PV panel" item, updated values and manufacturer information of C9 capacitor, updated "Technol. info." of J1, J2, J3 jumper, quantity of R6 item, item numbers and "More information" for several items). Minor modifications throughout document.
13-Nov-2014	3	Updated figure in cover page.

APPENDIX C: Technical details for Peltier Cooler Module

ET-063-10-13-H1
Peltier Cooler Module

Data sheet

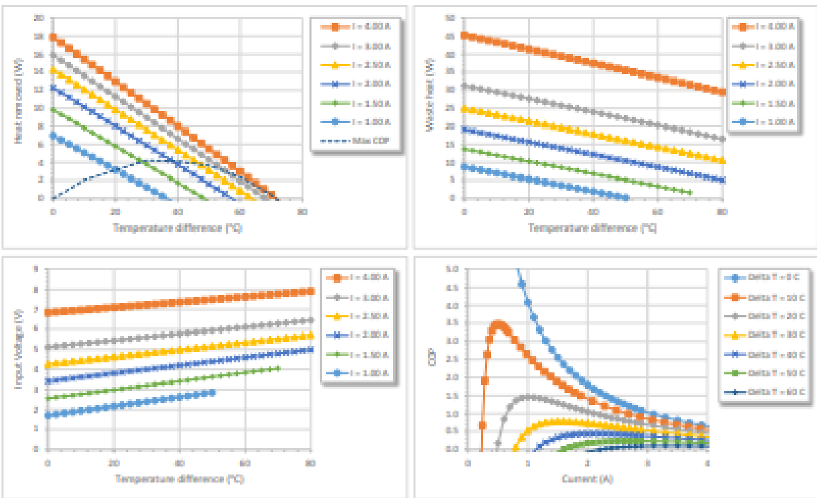


Imax	[A]	4.0
Vmax	[Vdc]	7.9
Pc max	[W]	18
ΔTmax	[°C]	73
A	[mm]	30
A1	[mm]	30
B	[mm]	15
H	[mm]	3.6
L	[mm]	100
Wire	AWG	n/a

- (At hot side temperature Th = 25°C / 298K, under dry N_2)
- Pc max = Cooling power at ΔT = 0 and I = Imax
- ΔTmax = Temperature difference at I = Imax and Pc = 0
- Max hot side temperature Th = 90°C for best long term performance
- Max mounting pressure: 1.5MPa
- Wires: UL-style 1569, 105°C (Unstripped)

ET-063-10-13-H1
Peltier Cooler Module

Data sheet - At hot side temperature 25°C



*Note - Waste heat = Heat out of hot side

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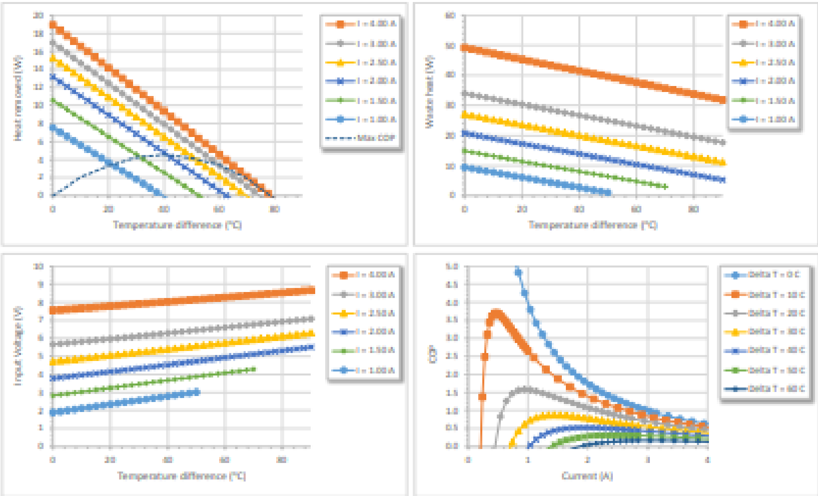
Version 1 -2018

ET-063-10-13-H1
Peltier Cooler Module

Data sheet - At hot side temperature 50°C

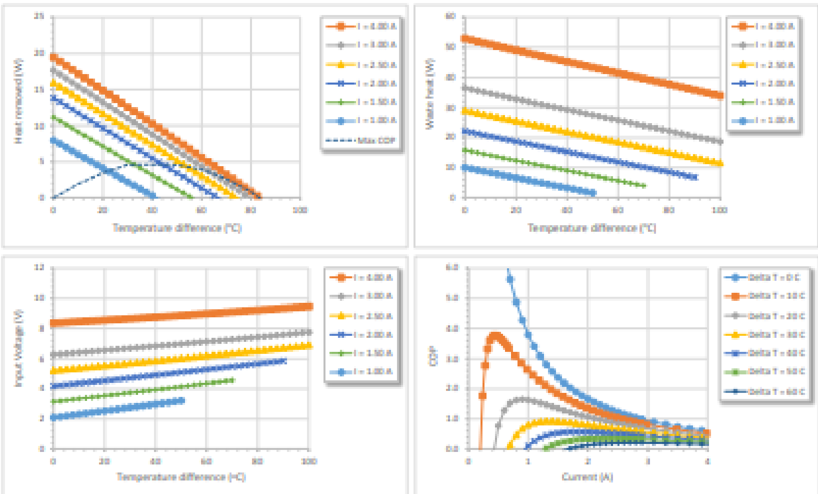


*Note - Waste heat = Heat out of hot side

Adaptive

ET-063-10-13-H1
Peltier Cooler Module

Data sheet - At hot side temperature 75°C



*Note - Waste heat = Heat out of hot side

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Version 1 -2018

APPENDIX D: Technical Details For ARUBA 303 series Campus access point (wireless router)

aruba
a Hewlett Packard Enterprise company

DATA SHEET

ARUBA 303 SERIES CAMPUS ACCESS POINTS

Low-cost 802.11ac Wave 2 (Wi-Fi 5) enterprise connectivity

The affordable mid-range Aruba 303 Series campus access point delivers high performance 802.11ac with MU-MIMO (Wave 2) for medium density enterprise environments. With the integrated BLE and supporting 802.3af power, the Aruba 303 Series AP enables enterprises to improve their work efficiency and productivity with the lowest TCO.

The compact Aruba 303 Series AP delivers a maximum concurrent data rate of 867 Mbps in the 5GHz band and 300 Mbps in the 2.4GHz band (for an aggregate peak data rate of 1.2Gbps). Featuring 2x2:2SS, the Aruba 303 is designed for medium device density environments, such as schools, retail branches, warehouses, hotels and enterprise offices, where the environment is cost sensitive.

IOT PLATFORM CAPABILITIES

The 303 Series includes an integrated Bluetooth 5 and 802.15.4 radio (for Zigbee support) to simplify deploying and managing Meridian and IoT-based location services, asset tracking services, security solutions and IoT sensors. This allows organizations to leverage the AP as an IoT platform, which eliminates the need for an overlay infrastructure and additional IT resources.

UNIQUE BENEFITS

- Unified AP – deploy with or without controller
  - The 303 Series access points can be deployed in either controller-based (ArubaOS) or controller-less (InstantOS) deployment mode
- Dual Radio 2x2 802.11ac access point with Multi-User MIMO (wave 2)
  - Supports up to 867Mbps in the 5GHz band (with 2SS/VHT80 client devices) and up to 300Mbps in the 2.4GHz band (with 2SS/HT40 clients)

KEY FEATURES

- Up to 1.2 Gbps aggregate peak data rate
- Daisy-chain another AP using the secondary PoE-out port
- Integrated Zigbee and Bluetooth 5 radio for IoT connectivity
- Resolve sticky client issues with MU-MIMO-aware ClientMatch
- Participates in Aruba's Dynamic Segmentation solution

- Built-in Bluetooth Low-Energy (BLE) radio
  - Enables location based services with BLE-enabled mobile devices receiving signals from multiple Aruba Beacons at the same time
  - Enables asset tracking when used with Aruba Asset Tags
- Advanced Cellular Coexistence (ACC)
  - Minimizes interference from 3G/4G cellular networks, distributed antenna systems and commercial small cell/femtocell equipment
- Quality of service for unified communications applications
  - Supports priority handling and policy enforcement for unified communication apps, including Skype for Business with encrypted videoconferencing, voice, chat and desktop sharing

- Aruba AppRF technology leverages deep packet inspection to classify and block, prioritize or limit bandwidth for over 2,500 enterprise apps or groups of apps
- RF Management
  - Adaptive Radio Management (ARM) technology with AirMatch automatically assigns channel, width and power settings based on environment and client density. It also provides airtime fairness and ensures that APs stay clear of all sources of RF interference to deliver reliable, high-performance WLANs
  - The Aruba 303 Series Access Points can be configured to provide part-time or dedicated air monitoring for spectrum analysis and wireless intrusion protection, VPN tunnels to extend remote locations to corporate resources, and wireless mesh connections where Ethernet drops are not available
- Spectrum analysis
  - Capable of part-time or dedicated air monitoring, the spectrum analyzer remotely scans the 2.4GHz and 5GHz radio bands to identify sources of RF interference from HT20 through VHT80 operation
- Aruba Secure Core
  - Device assurance: Use of Trusted Platform Module (TPM) for secure storage of credentials and keys as well as secure boot
  - Integrated wireless intrusion protection offers threat protection and mitigation, and eliminates the need for separate RF sensors and security appliances
  - IP reputation and security services identify, classify, and block malicious les, URLs and IPs, providing comprehensive protection against advanced online threats

Daisy-chain your wired network to connect and power any network device (IP camera, IOT gateway, or even a second Access Point) to the E1 Ethernet port of the AP-303P. Simplify and cost-reduce the installation of multiple devices by sharing switch ports and cabling.

CHOOSE YOUR OPERATING MODE

The Aruba 303 Series Access Points offer a choice of deployment and operating modes to meet your unique management and deployment requirements:

- The 303 Series AP is a unified AP that supports both controller-based and controller-less deployment modes, providing maximum flexibility.
- Controller-based mode – When deployed in conjunction with an Aruba Mobility Controller, Aruba 303 Series Access Points offer centralized configuration, data encryption, policy enforcement and network services, as well as distributed and centralized traffic forwarding.
- Controller-less (Instant) mode – The controller function is virtualized in a cluster of APs in Instant mode. As the network grows and/or requirements change, Instant deployments can easily migrate to controller-based mode.
- Remote AP (RAP) mode for branch deployments
- Air monitor (AM) for wireless IDS, rogue detection and containment
- Spectrum analyzer (SA), dedicated or hybrid, for identifying sources of RF interference
- Secure enterprise mesh portal or point

For large installations across multiple sites, the Aruba Activate service significantly reduces deployment time by automating device provisioning, firmware upgrades, and inventory management. With Aruba Activate, the APs can be factory-shipped to any site and configure themselves when powered up.

SPECIFICATIONS

Hardware Variants

- AP-303 models: single Ethernet
- AP-303P models: second Ethernet with PoE out

Wi-Fi Radio Specifications

- AP type: Indoor, dual radio, 5GHz 802.11ac 2x2 MIMO and 2.4GHz 802.11n 2x2 MIMO
- 5GHz (radio 0):
  - Two spatial stream Single User (SU) MIMO for up to 867 Mbps wireless data rate to individual 2SS VHT80 client devices
  - Two spatial stream Multi User (MU) MIMO for up to 867 Mbps wireless data rate to two 1SS MU-MIMO capable client devices simultaneously
- 2.4GHz (radio 1):
  - Two spatial stream Single User (SU) MIMO for up to 300 Mbps wireless data rate to individual 2SS HT40 client devices
- Support for up to 256 associated client devices per radio, and up to 16 BSSIDs per radio
- Supported frequency bands (country-specific restrictions apply):
  - 2.400 to 2.4835GHz
  - 5.150 to 5.250GHz
  - 5.250 to 5.350GHz
  - 5.470 to 5.725GHz
  - 5.725 to 5.850GHz

- Available channels: Dependent on configured regulatory domain
- Dynamic frequency selection (DFS) optimizes the use of available RF spectrum
- Supported radio technologies:
  - 802.11b: Direct-sequence spread-spectrum (DSSS)
  - 802.11a/g/n/ac: Orthogonal frequency-division multiplexing (OFDM)
- Supported modulation types:
  - 802.11b: BPSK, QPSK, CCK
  - 802.11a/g/n/ac: BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM
- Transmit power: Configurable in increments of 0.5dBm
- Maximum (aggregate, conducted total) transmit power (limited by local regulatory requirements):
  - 2.4GHz band: +21dBm (18dBm per chain)
  - 5GHz band: +21dBm (18dBm per chain)
  - Note: conducted transmit power levels exclude antenna gain. For total (EIRP) transmit power, add antenna gain
- Advanced Cellular Coexistence (ACC) minimizes the impact of interference from cellular networks
- Maximum ratio combining (MRC) for improved receiver performance
- Cyclic delay/shift diversity (CDD/CSD) for improved downlink RF performance
- Short guard interval for 20MHz, 40MHz and 80MHz channels
- Space-time block coding (STBC) for increased range and improved reception
- Low-density parity check (LDPC) for high-efficiency error correction and increased throughput
- Transmit beam-forming (TxBF) for increased signal reliability and range
- Supported data rates (Mbps):
  - 802.11b: 1, 2, 5.5, 11
  - 802.11a/g: 6, 9, 12, 18, 24, 36, 48, 54
  - 802.11n: 6.5 to 300 (MCS0 to MCS15)
  - 802.11ac: 6.5 to 867 (MCS0 to MCS9, NSS = 1 to 2)
  - 802.11n high-throughput (HT) support: HT20/40
  - 802.11ac very high throughput (VHT) support: VHT20/40/80
  - 802.11n/ac packet aggregation: A-MPDU, A-MSDU

Wi-Fi Antennas

- Two vertically polarized dual-band downtilt omni-directional antennas for 2x2 MIMO with peak antenna gain of:
  - 3.3dBi in 2.4GHz and 5.8dBi in 5GHz for AP-303
  - 3.4dBi in 2.4GHz and 7.8dBi in 5GHz for AP-303P
- The antennas are optimized for horizontal ceiling mounted orientation of the AP. The downtilt angle for maximum gain is roughly 30 degrees.
- Combining the patterns of both antennas per radio, the peak gain of the average (effective) pattern is:
  - 2.1dBi in 2.4GHz and 5.7dBi in 5GHz for AP-303
  - 2.1dBi in 2.4GHz and 5.9dBi in 5GHz for AP-303P

Other Interfaces

- E0: One 10/100/1000BASE-T Ethernet network interface (RJ-45)
  - Auto-sensing link speed and MDI/MDX
  - 802.3az Energy Efficient Ethernet (EEE)
  - PoE-PD: 48Vdc (nominal) 802.3af/at/bt PoE
- DC power interface
- E1 (AP-303P models only): One 10/100/1000BASE-T Ethernet network interface (RJ-45)
  - Auto-sensing link speed and MDI/MDX
  - 802.3az Energy Efficient Ethernet (EEE)
  - PoE-PSE (output): 48Vdc (nominal) 802.3af/at PoE
- Bluetooth Low Energy (BLE) radio
- Zigbee 802.15.4 radio (AP-303P models only)
- Visual indicators (tri-color LEDs): for System and Radio status
- Reset button: factory reset (during device power-up), LED mode control (normal/off)
- Serial console interface (proprietary, µUSB physical jack)
- Kensington security slot

Power Sources and Consumption

- The AP supports direct DC power and Power over Ethernet (PoE)
- When both power sources are available, DC power takes priority over PoE
- Power sources are sold separately

-303 models:

- Direct DC source: 12Vdc nominal, +/- 5%
- DC power interface accepts 2.1/5.5-mm center-positive circular plug with 9.5-mm length
- Power over Ethernet (PoE): 48Vdc (nominal) 802.3af compliant source
- Maximum (worst-case) power consumption: 10.1W (PoE) or 8.8W (DC)
- Maximum (worst-case) power consumption in idle mode: 4.2W (PoE) or 4.0W (DC)

-303P models:

- Direct DC source: 48Vdc nominal, +/- 5%
- DC power interface accepts 1.35/3.5-mm center-positive circular plug with 9.5-mm length
- Power over Ethernet (PoE-PD) on E0: 48Vdc (nominal) 802.3af/at/bt compliant source
- PoE-PSE function on E1 disabled when powered by 802.3af PoE, limited to class 3 when powered by 802.3at PoE, unrestricted when powered by 802.3bt PoE or DC
- Maximum (worst-case) power consumption: 11.3 (PoE) or 11.5 (DC)
- Maximum (worst-case) power consumption in idle mode: 6.8 (PoE) or 7.0 (DC)
- Power consumption numbers exclude power to support PoE-PSE function on E1

ounting

- The AP ships with a (black) mount clips to attach to a 9/16-inch or 15/16-inch flat T-bar drop-tile ceiling
- Several optional mount kits are available to attach the AP to a variety of surfaces; see the Ordering Information section below for details

echanical

- Dimensions and weight (unit, excluding mount accessories):
  - 150mm (W) x 150mm (D) x 35mm (H) or 5.9" (W) x 5.9" (D) x 1.4" (H)
  - AP-303 models: 260g or 9.2oz
  - AP-303P models: 280g or 9.9oz
- Dimensions and weight (shipping):
  - 190mm (W) x 180mm (D) x 60mm (H) or 7.4" (W) x 7.0" (D) x 2.4" (H)
  - AP-303 models: 410g or 14.5oz
  - AP-303P models: 430g or 15.2oz

Environmental

- Operating:
  - Temperature: 0° C to +40° C (+32° F to +104° F)
  - Humidity: 5% to 93% non-condensing
- Storage and transportation:
  - Temperature: -40° C to +70° C (-40° F to +158° F)

Reliability (at +25C operating temperature)

- AP-303 models MTBF: 795khrs (91yrs)
- AP-303P models MTBF: 518khrs (59yrs)

Regulatory

- FCC/ISED
- CE Marked
- RED Directive 2014/53/EU
- EMC Directive 2014/30/EU
- Low Voltage Directive 2014/35/EU
- UL/IEC/EN 60950
- EN 60601-1-1 and EN 60601-1-2
- EN 50155 (AP-303)

For more country-specific regulatory information and approvals, please see your Aruba representative.

Regulatory Model Numbers

- AP-303: APIN0303
- AP-303P: APINP303

Certifications

- CB Scheme Safety, cTUVus
- UL2043 plenum rating
- Wi-Fi Alliance (WFA) certified 802.11a/b/g/n/ac
- WPA, WPA2 and WPA3 – Enterprise with CNSA option, Personal (SAE), Enhanced Open (OWE)
- Wi-Fi Alliance certified (WFA) 802.11ac with Wave 2 features
- Passpoint® (Release 2) with ArubaOS and Instant 8.3+

WARRANTY

- Aruba limited lifetime warranty

MINIMUM SOFTWARE VERSIONS

- AP-303 models: ArubaOS & Aruba InstantOS 8.3.0.0
- AP-303P models: ArubaOS & Aruba InstantOS 8.4.0.0

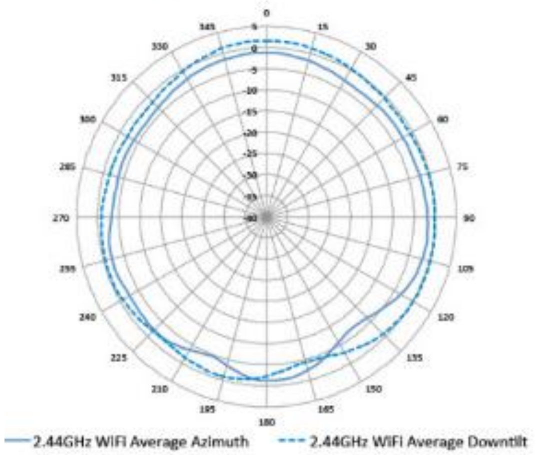
RF PERFORMANCE TABLE	Maximum transmit power (dBm) per transmit chain	Receiver sensitivity (dBm) per receive chain
802.11b 2.4GHz		
1 Mbps	18.0	-93.0
11 Mbps	18.0	-87.0
802.11g 2.4GHz		
6 Mbps	18.0	-90.0
54 Mbps	16.0	-73.0
802.11n HT20 2.4GHz		
MCS0/8	18.0	-90.0
MCS7/15	14.0	-71.0
802.11n HT40 2.4GHz		
MCS0/8	18.0	-87.0
MCS7/15	14.0	-68.0
802.11a 5GHz		
6 Mbps	18.0	-90.0
54 Mbps	16.0	-73.0
802.11n HT20 5GHz		
MCS0/8	18.0	-90.0
MCS7/15	14.0	-71.0
802.11n HT40 5GHz		
MCS0/8	18.0	-87.0
MCS7/15	14.0	-68.0
802.11ac VHT20 5GHz		
MCS0	18.0	-90.0
MCS9	12.0	-67.0
802.11ac VHT40 5GHz		
MCS0	18.0	-87.0
MCS9	12.0	-62.0
802.11ac VHT80 5GHz		
MCS0	18.0	-84.0
MCS9	12.0	-59.0

ote: Table shows the maximum hardware capability of the AP (excluding antenna and MIMO/MRC gain). Actual maximum transmit power may be limited below these umbers to ensure compliance with local regulatory requirements.

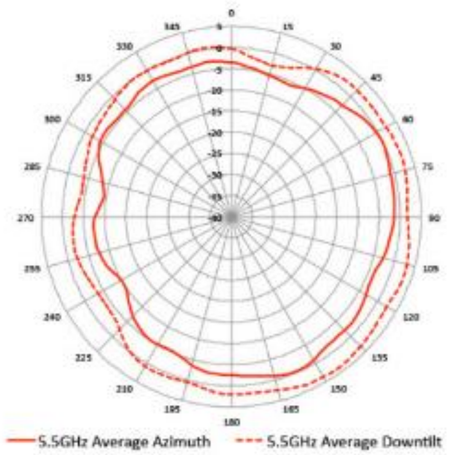
ANTENNA PATTERN PLOTS

Horizontal planes (top view, AP facing forward)

Showing both azimuth (0 degrees) and 30 degrees downtilt patterns



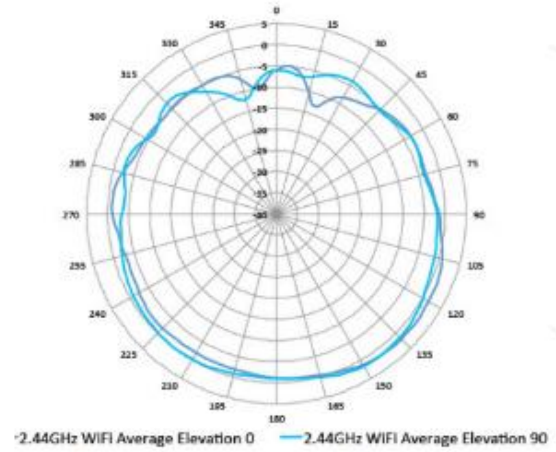
2.44GHz Wi-Fi (radio 1)



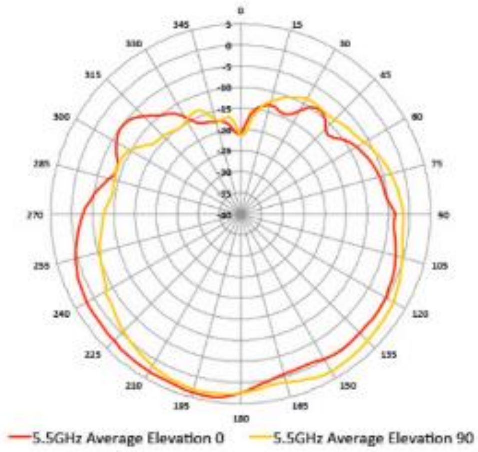
5.5GHz Wi-Fi (radio 0)

Elevation planes (side view, AP facing down)

Showing side view with AP rotated 0 and 90 degrees



2.44GHz Wi-Fi (radio 1)



5.5GHz Wi-Fi (radio 0)

ORDERING INFORMATION

?art Number	Description
Aruba 303 Series Campus Access Points	
Z317A	Aruba AP-303 (EG) Dual 2x2:2 MU-MIMO Radio Internal Antennas Unified Campus AP
Z318A	Aruba AP-303 (IL) Dual 2x2:2 MU-MIMO Radio Internal Antennas Unified Campus AP
Z319A	Aruba AP-303 (JP) Dual 2x2:2 MU-MIMO Radio Internal Antennas Unified Campus AP
Z320A	Aruba AP-303 (RW) Dual 2x2:2 MU-MIMO Radio Internal Antennas Unified Campus AP
Z321A	Aruba AP-303 (US) Dual 2x2:2 MU-MIMO Radio Internal Antennas Unified Campus AP
Z320ACM	Aruba CM AP-303 (RW) Dual 2x2:2 MU-MIMO Radio Internal Antennas Unified Campus AP
Z321ACM	Aruba CM AP-303 (US) Dual 2x2:2 MU-MIMO Radio Internal Antennas Unified Campus AP
Aruba 303P Series Campus Access Points	
?0G65A	Aruba AP-303P (EG) Dual 2x2:2 MU-MIMO Radio Internal Antennas Unified Campus AP Dual Ethernet
?0G66A	Aruba AP-303P (IL) Dual 2x2:2 MU-MIMO Radio Internal Antennas Unified Campus AP Dual Ethernet
?0G67A	Aruba AP-303P (JP) Dual 2x2:2 MU-MIMO Radio Internal Antennas Unified Campus AP Dual Ethernet
?0G68A	Aruba AP-303P (RW) Dual 2x2:2 MU-MIMO Radio Internal Antennas Unified Campus AP Dual Ethernet
?0G69A	Aruba AP-303P (US) Dual 2x2:2 MU-MIMO Radio Internal Antennas Unified Campus AP Dual Ethernet
?2H41A	Aruba AP-303P (EG) TAA Dual 2x2:2 MU-MIMO Radio Internal Antennas Unified Campus AP Dual Ethernet
?2H42A	Aruba AP-303P (IL) TAA Dual 2x2:2 MU-MIMO Radio Internal Antennas Unified Campus AP Dual Ethernet
?2H43A	Aruba AP-303P (JP) TAA Dual 2x2:2 MU-MIMO Radio Internal Antennas Unified Campus AP Dual Ethernet
?2H44A	Aruba AP-303P (RW) TAA Dual 2x2:2 MU-MIMO Radio Internal Antennas Unified Campus AP Dual Ethernet
?2H45A	Aruba AP-303P (US) TAA Dual 2x2:2 MU-MIMO Radio Internal Antennas Unified Campus AP Dual Ethernet

ote: All hardware SKUs can be managed by Aruba Central. Central Managed (CM) SKUs are used for simplified ordering within US and Canada only.

or more ordering information and compatible accessories, please refer to the **ordering guide.**

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DS_AP303Series_RVK_120221 a00059875enw

Contact Us Share

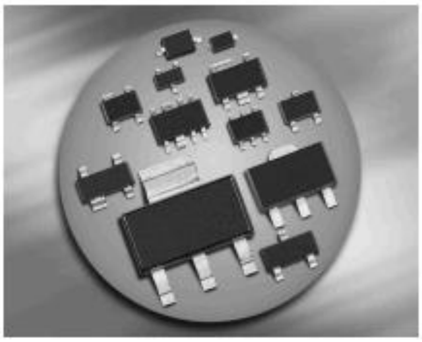
APPENDIX E: Technical Details for Silicon Schottky Diode for RF Rectifier

BAT62...

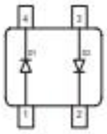
Silicon Schottky Diode

- Low barrier diode for detectors up to GHz frequencies
- Pb-free (RoHS compliant) package

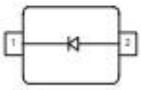
RoHS



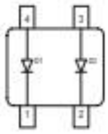
BAT62



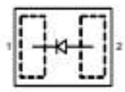
BAT62-03W
BAT62-02V
BAT62-02W



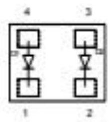
BAT62-07W



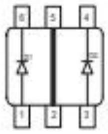
BAT62-02L
BAT62-02LS



BAT62-07L4



BAT62-09S



ESD (**E**lectro**s**tatic **d**ischarge) sensitive device, observe handling precaution!

Type	Package	Configuration	L_S(nH)	Marking
BAT62-02W**	SCD80	single	0.6	62
BAT62	SOT143	anti-parallel pair	2	62s
BAT62-02L	TSLP-2-1	single, leadless	0.4	L
BAT62-02LS*	TSSLP-2-1	single, leadless	0.2	U
BAT62-02V	SC79	single	0.6	k
BAT62-03W	SOD323	single	1.8	white L
BAT62-07L4	TSLP-4-4	parallel pair, leadless	0.4	62
BAT62-07W	SOT343	parallel pair	1.8	62s
BAT62-09S	SOT363	parallel high, high isolation	1.6	69s

* Preliminary Data
** Not for new design

Maximum Ratings at T_A = 25 °C, unless otherwise specified

Parameter	Symbol	Value	Unit
Diode reverse voltage	V_R	40	V
Forward current	I_F	20	mA
Total power dissipation	P_{tot}		mW
BAT62, $T_S \leq$ 85 °C		100	
BAT62-02L, -07L4, -03W, $T_S \leq$ 108 °C		100	
BAT62-02W, -02V, $T_S \leq$ 109 °C		100	
BAT62-07W, $T_S \leq$ 103 °C		100	
BAT62-09S, $T_S \leq$ 105 °C		100	
Junction temperature	T_j	150	°C
Storage temperature	T_{stg}	-55 ... 150	

Thermal Resistance

Parameter	Symbol	Value	Unit
Junction - soldering point[1]	R_{thJS}		
BAT62		≤ 650	
BAT62-02L, -07L4, -03W		≤ 420	
BAT62-02W, 02V		≤ 410	
BAT62-07W		≤ 470	
BAT62-09S		≤ tbd	

Electrical Characteristics at T_A = 25 °C, unless otherwise specified

Parameter	Symbol	Values			Unit
		min.	typ.	max.	
DC Characteristics					
Reverse current V_R = 40 V	I_R	-	-	10	µA
Forward voltage I_F = 2 mA	V_F	-	0.58	1	V
Forward voltage matching[2)] I_F = 2 mA	ΔV_F	-	-	20	mV

[1]For calculation of R_{thJA} please refer to Application Note AN077 (Thermal Resistance Calculation)

[2]ΔV_F is the difference between lowest and highest V_F in a multiple diode component.

Electrical Characteristics at T_A = 25 °C, unless otherwise specified

Parameter	**Symbol**	**Values**			**Unit**
		min.	**typ.**	**max.**	
AC Characteristics					
Diode capacitance V_R = 0 V, f = 1 MHz	C_T	-	0.35	0.6	pF
Differential resistance V_R = 0 V, f = 10 kHz	R_0	-	225	-	kΩ

Maximum Ratings at T_A = 25 °C, unless otherwise specified

Parameter	Symbol	Value	Unit
Diode reverse voltage	V_R	40	V
Forward current	I_F	20	mA
Total power dissipation	P_{tot}		
BAT62, $T_S \leq$ 85 °C		100	
BAT62-02L, -07L4, -03W, $T_S \leq$ 108 °C		100	
BAT62-02W, -02V, $T_S \leq$ 109 °C		100	
BAT62-07W, $T_S \leq$ 103 °C		100	
BAT62-09S, $T_S \leq$ 105 °C		100	
Junction temperature	T_j	150	°C
Storage temperature	T_{stg}	-55 ... 150	

Thermal Resistance

Parameter	Symbol	Value	Unit
Junction - soldering point[1]	R_{thJS}		
BAT62		≤ 650	
BAT62-02L, -07L4, -03W		≤ 420	
BAT62-02W, 02V		≤ 410	
BAT62-07W		≤ 470	
BAT62-09S		≤ tbd	

Electrical Characteristics at T_A = 25 °C, unless otherwise specified

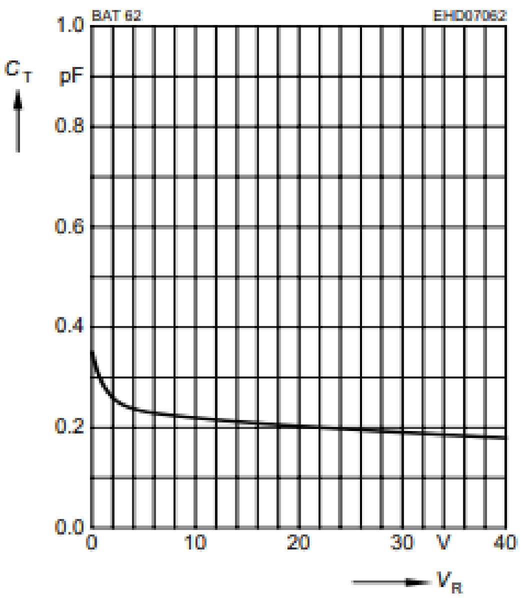
Parameter	Symbol	Values			Unit
		min.	typ.	max.	
DC Characteristics					
Reverse current V_R = 40 V	I_R	-	-	10	µA
Forward voltage I_F = 2 mA	V_F	-	0.58	1	V
Forward voltage matching[2] I_F = 2 mA	ΔV_F	-	-	20	mV

[1] For calculation of R_{thJA} please refer to Application Note AN077 (Thermal Resistance Calculation)

[2] ΔV_F is the difference between lowest and highest V_F in a multiple diode component.

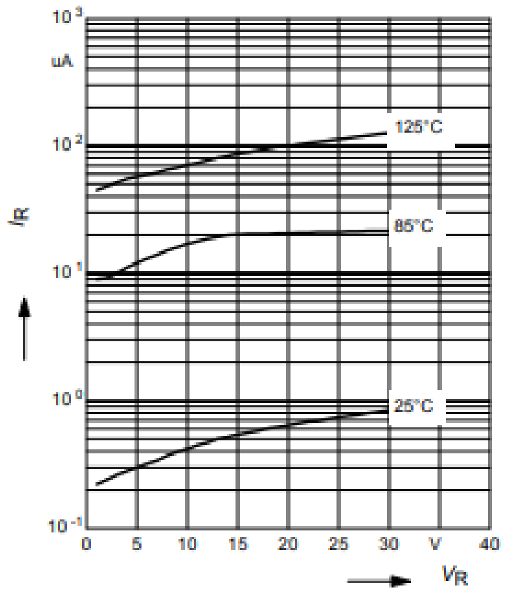
Diode capacitance $C_T = f(V_R)$

f = 1MHz



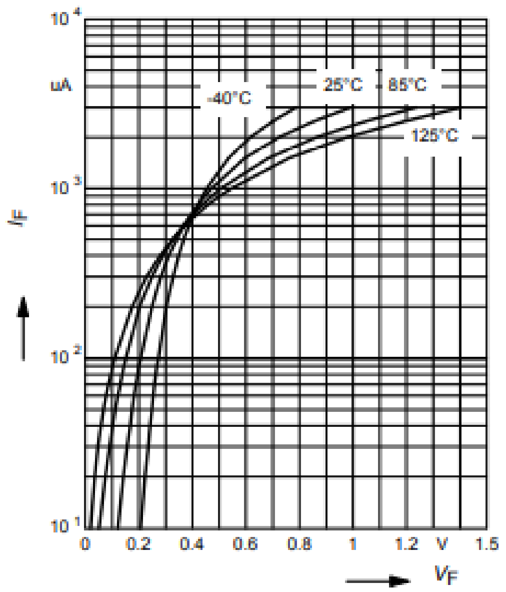
Reverse current $I_R = f(V_R)$

T_A = Parameter



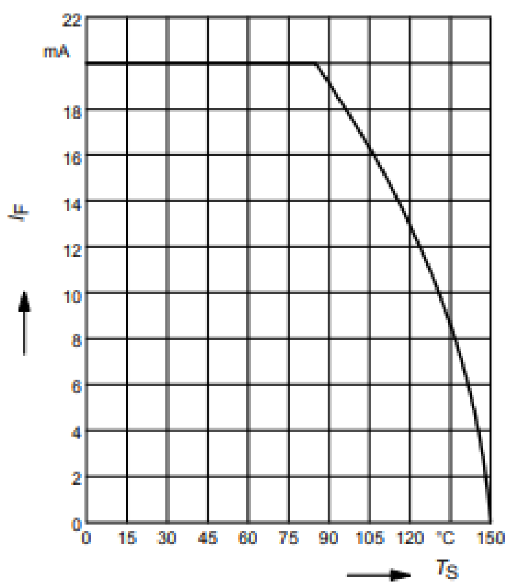
Forward current $I_F = f(V_F)$

T_A = Parameter

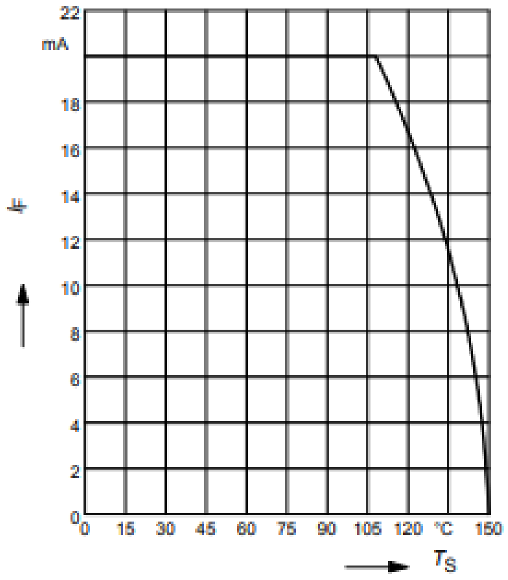


Forward current $I_F = f(T_S)$

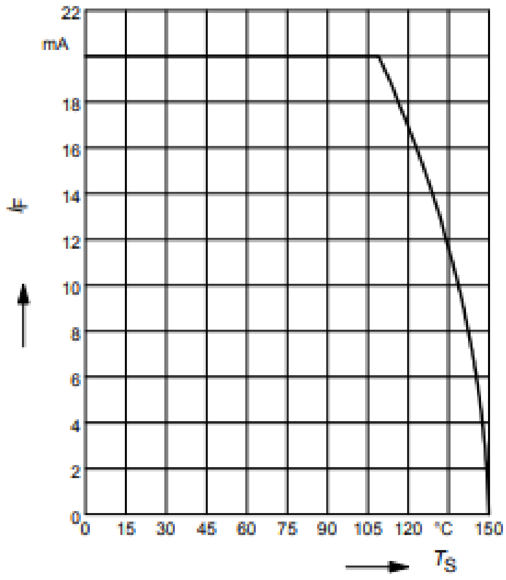
BAT62



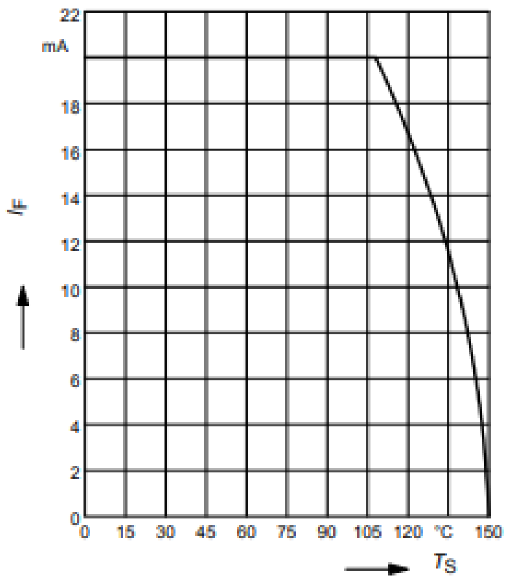
Forward current $I_F = f(T_S)$
BAT62-02L, -07L4



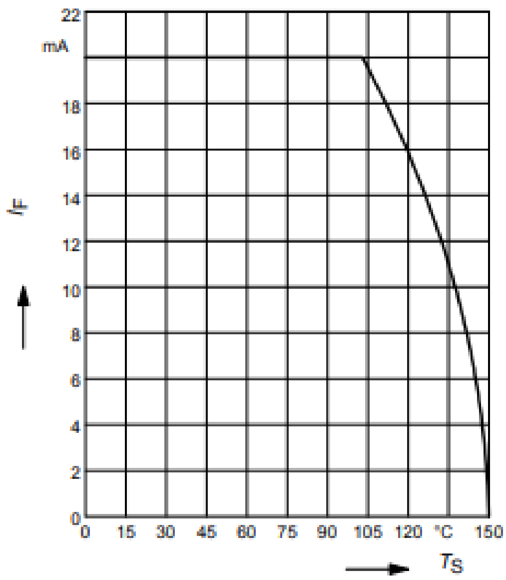
Forward current $I_F = f(T_S)$
BAT62-02W, -02V



Forward current $I_F = f(T_S)$
BAT62-03W

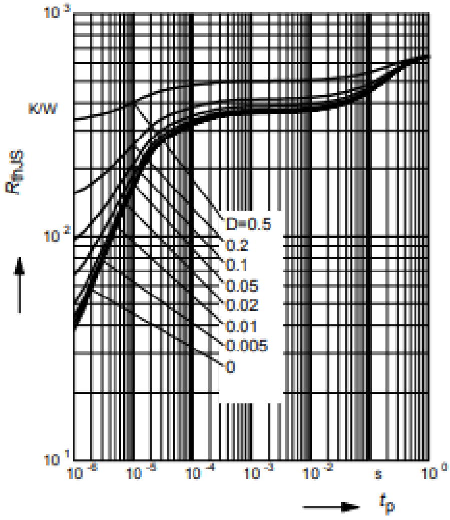


Forward current $I_F = f(T_S)$
BAT62-07W



Permissible Puls Load $R_{thJS} = f\ (t_p)$

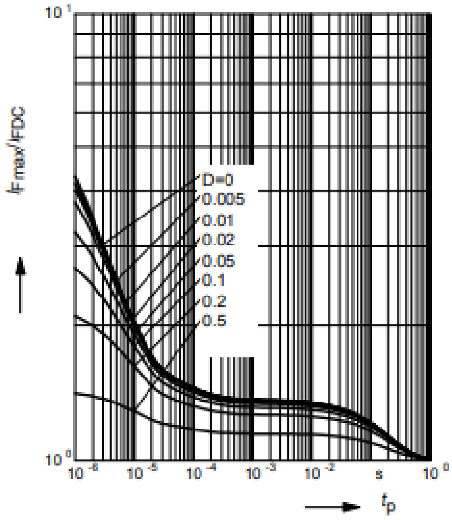
BAT62



Permissible Pulse Load

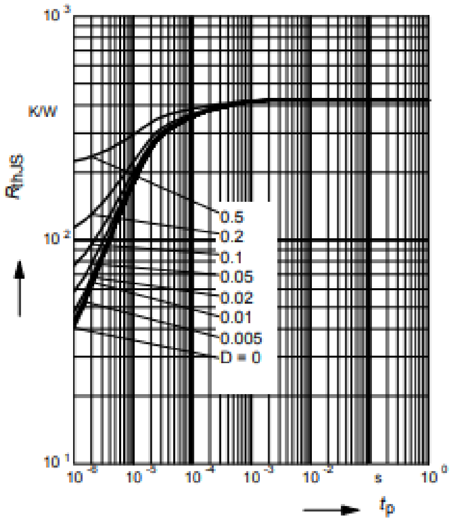
$I_{Fmax}/\ I_{FDC} = f\ (t_p)$

BAT62



Permissible Puls Load $R_{thJS} = f\ (t_p)$

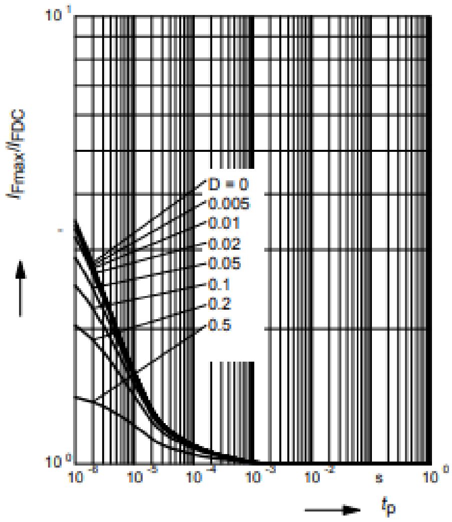
BAT62-02L, -07L4



Permissible Pulse Load

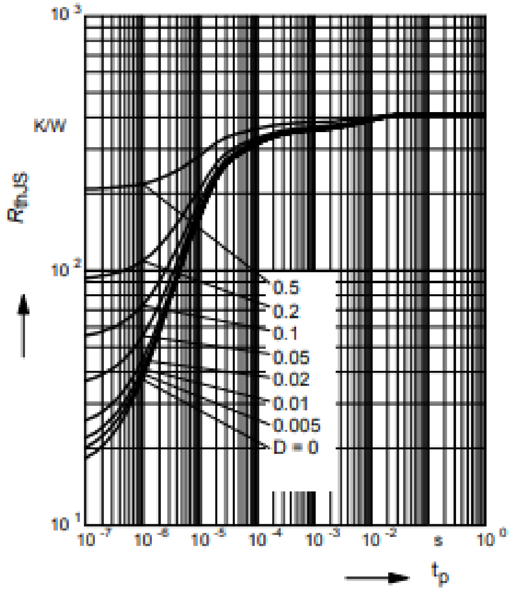
$I_{Fmax}/\ I_{FDC} = f\ (t_p)$

BAT62-02L, -07L4



Permissible Puls Load $R_{thJS} = f(t_p)$

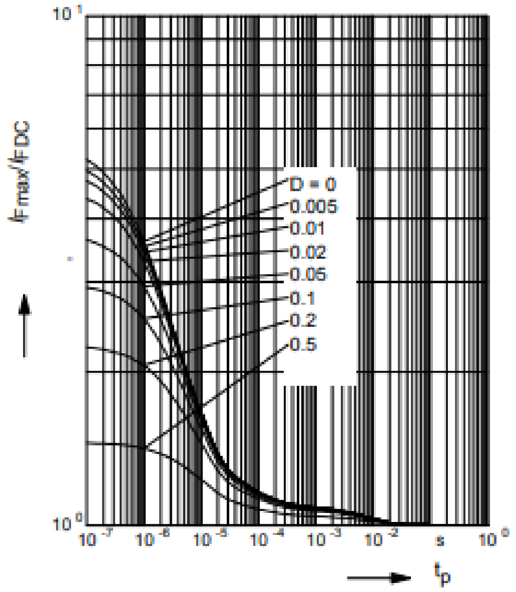
BAT62-02W, 02V



Permissible Pulse Load

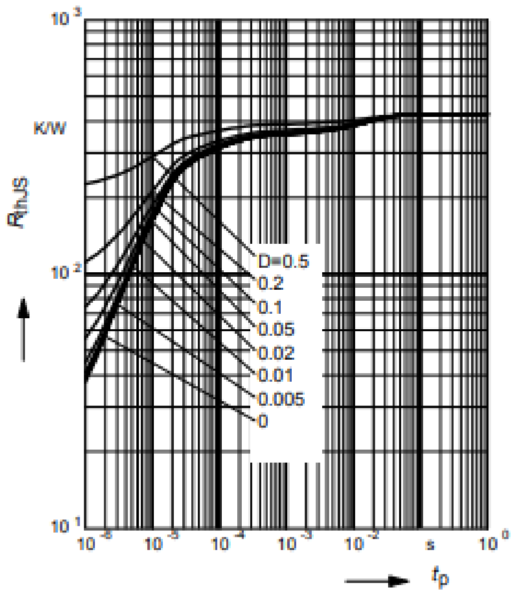
$I_{Fmax}/I_{FDC} = f(t_p)$

BAT62-02W, -02V



Permissible Puls Load $R_{thJS} = f(t_p)$

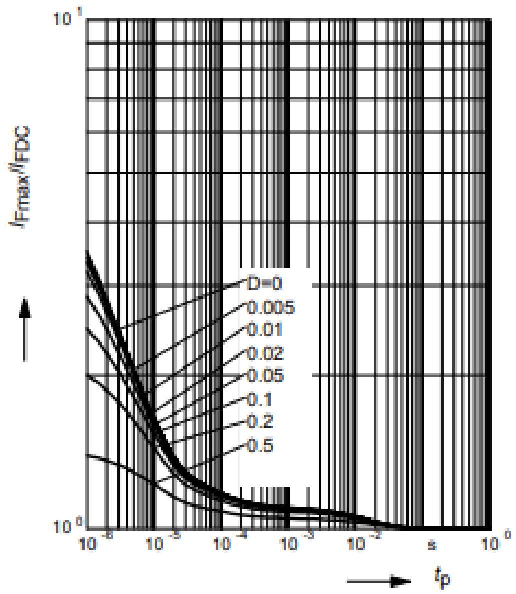
BAT62-03W



Permissible Pulse Load

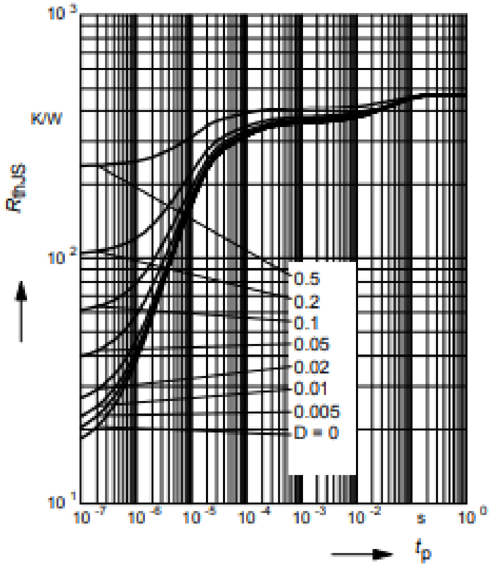
$I_{Fmax}/I_{FDC} = f(t_p)$

BAT62-03W



Permissible Puls Load $R_{thJS} = f(t_p)$

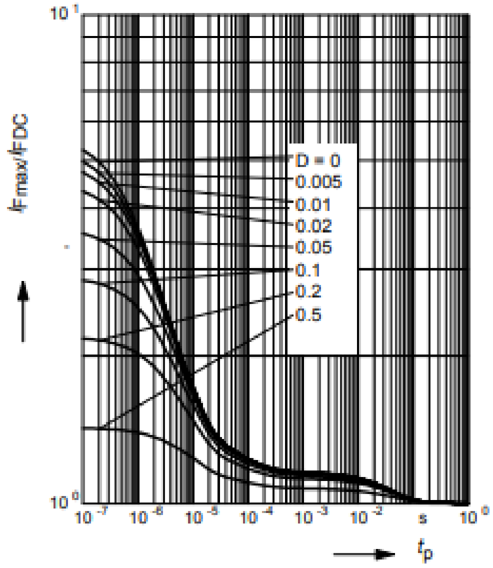
BAT62-07W



Permissible Pulse Load

$I_{Fmax}/I_{FDC} = f(t_p)$

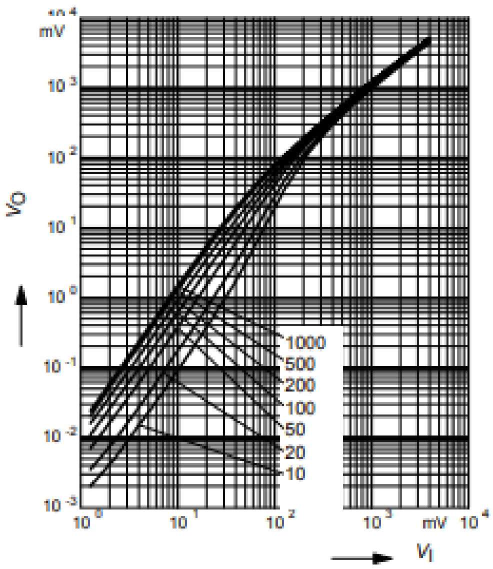
BAT62-07W



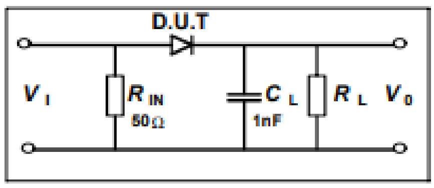
Rectifier voltage $V_{out} = f(V_{in})$

f = 900MHz

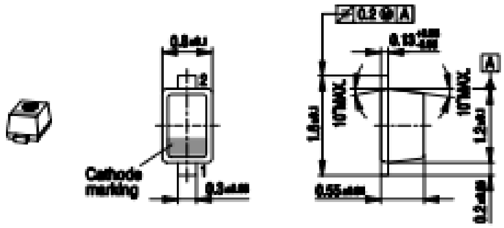
R_L = Parameter in kΩ



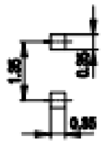
Testcircuit



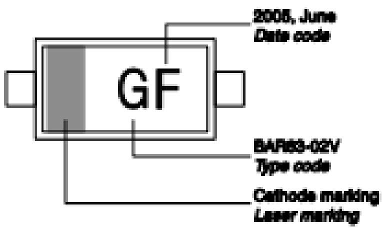
Package Outline



Foot Print

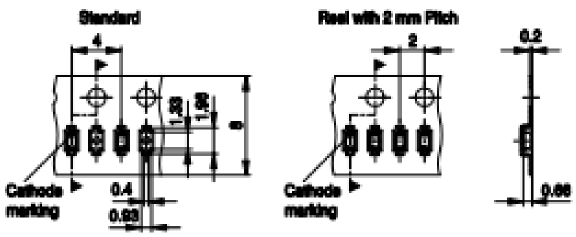


Marking Layout (Example)

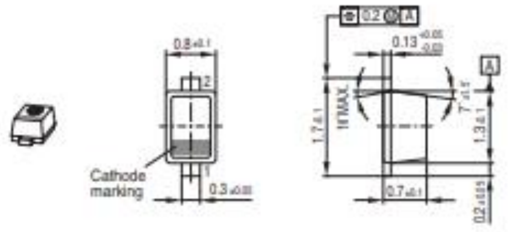


Standard Packing

Reel ø180 mm = 3.000 Pieces/Reel
Reel ø180 mm = 8.000 Pieces/Reel (2 mm Pitch)
Reel ø330 mm = 10.000 Pieces/Reel

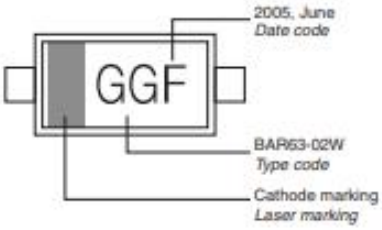


Package Outline



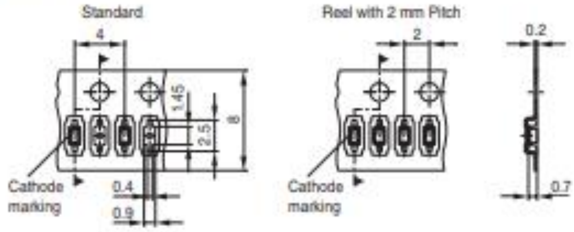
Foot Print

Marking Layout (Example)



Standard Packing

Reel ø180 mm = 3.000 Pieces/Reel
Reel ø180 mm = 8.000 Pieces/Reel (2 mm Pitch)
Reel ø330 mm = 10.000 Pieces/Reel

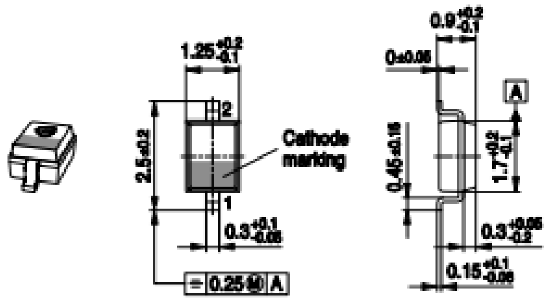


Date Code marking for discrete packages with one digit (SCD80, SC79, SC75[1)]) CES-Code

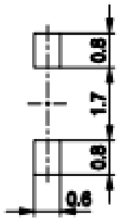
Month	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
01	a	p	A	P	a	p	A	P	a	p	A	P
02	b	q	B	Q	b	q	B	Q	b	q	B	Q
03	c	r	C	R	c	r	C	R	c	r	C	R
04	d	s	D	S	d	s	D	S	d	s	D	S
05	e	t	E	T	e	t	E	T	e	t	E	T
06	f	u	F	U	f	u	F	U	f	u	F	U
07	g	v	G	V	g	v	G	V	g	v	G	V
08	h	x	H	X	h	x	H	X	h	x	H	X
09	j	y	J	Y	j	y	J	Y	j	y	J	Y
10	k	z	K	Z	k	z	K	Z	k	z	K	Z
11	l	2	L	4	l	2	L	4	l	2	L	4
12	n	3	N	5	n	3	N	5	n	3	N	5

1) New Marking Layout for SC75, implemented at October 2005.

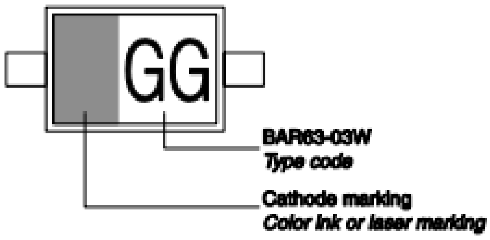
Package Outline



Foot Print

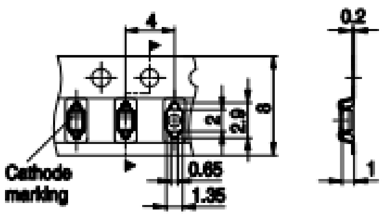


Marking Layout (Example)

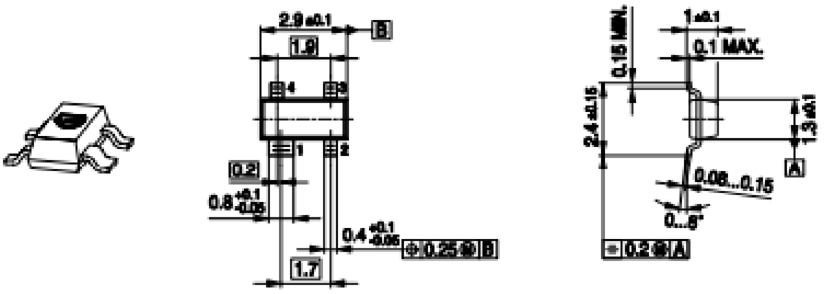


Standard Packing

Reel ø180 mm = 3.000 Pieces/Reel
Reel ø330 mm = 10.000 Pieces/Reel

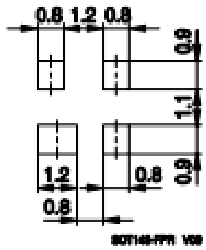


Package Outline

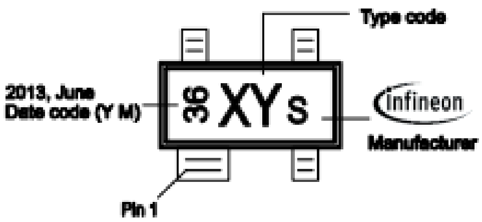


Note: Mold flash, protrusions or gate burrs of 0,2 mm max. per side are not included

Foot Print

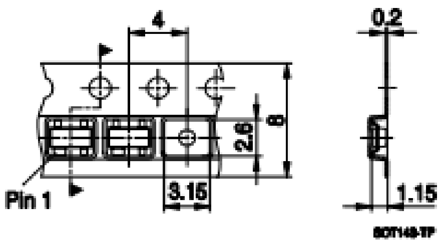


Marking Layout (Example)

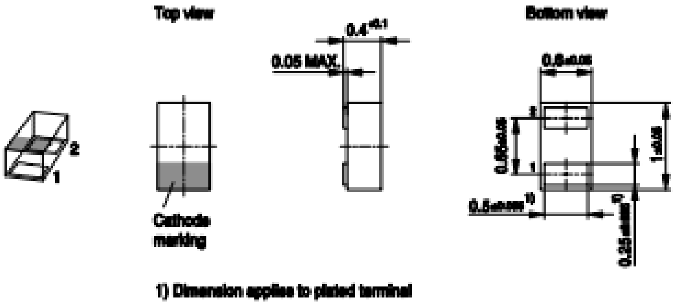


Standard Packing

Reel ø180 mm = 3.000 Pieces/Reel
Reel ø330 mm = 10.000 Pieces/Reel

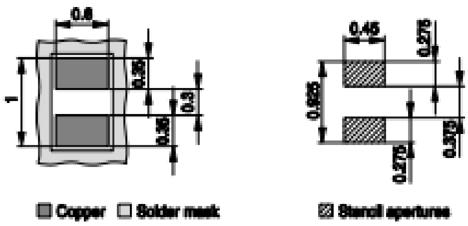


Package Outline

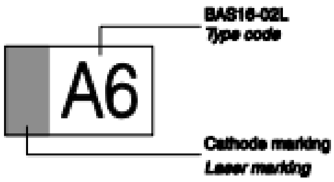


Foot Print

For board assembly information please refer to Infineon website "Packages"

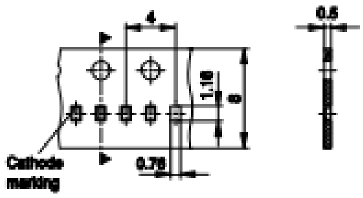


Marking Layout (Example)

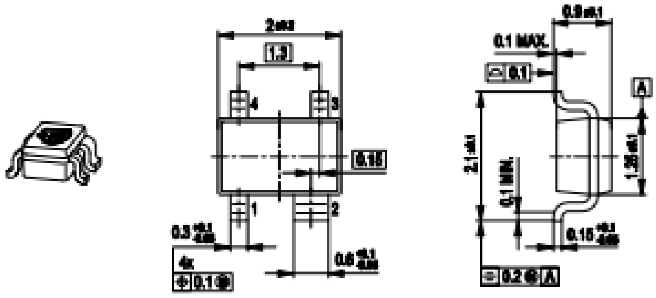


Standard Packing

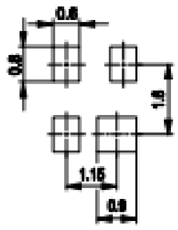
Reel ø180 mm = 15.000 Pieces/Reel
Reel ø330 mm = 50.000 Pieces/Reel (optional)



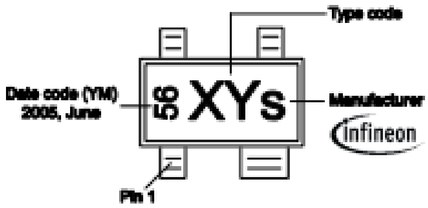
Package Outline



Foot Print

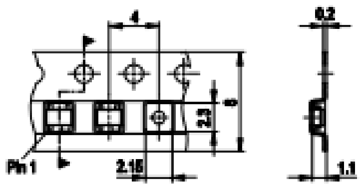


Marking Layout (Example)

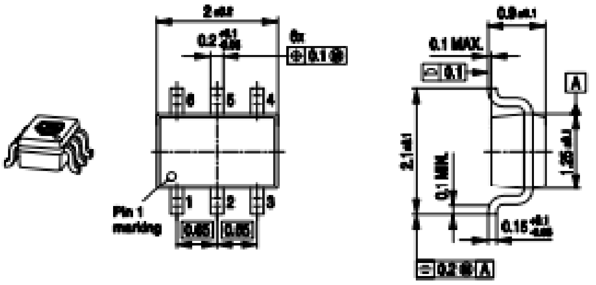


Standard Packing

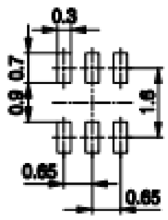
Reel ø180 mm = 3.000 Pieces/Reel
Reel ø330 mm = 10.000 Pieces/Reel



Package Outline

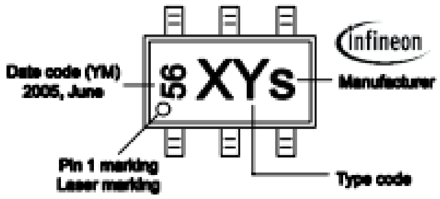


Foot Print



Marking Layout (Example)

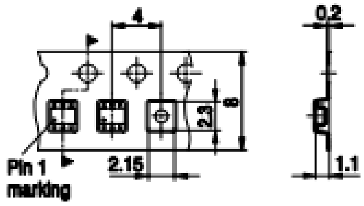
Small variations in positioning of
Date code, Type code and Manufacture are possible.



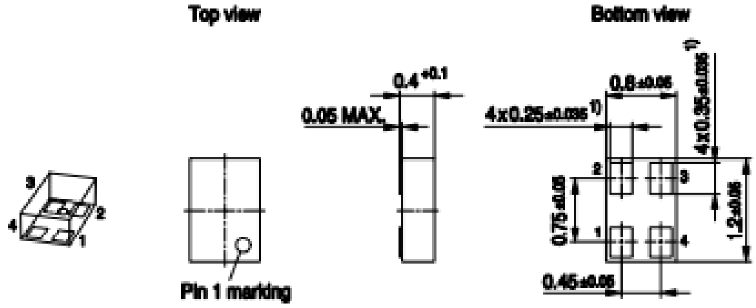
Standard Packing

Reel ø180 mm = 3.000 Pieces/Reel
Reel ø330 mm = 10.000 Pieces/Reel

For symmetric types no defined Pin 1 orientation in reel.



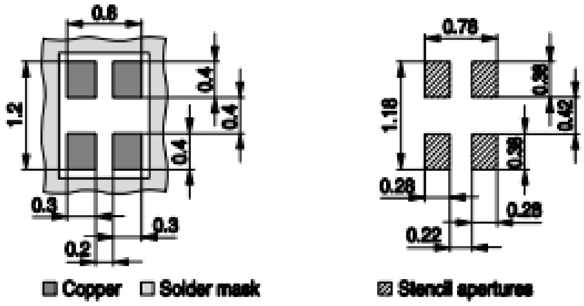
Package Outline



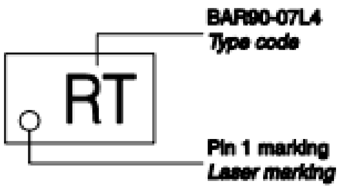
1) Dimension applies to plated terminal

Foot Print

For board assembly information please refer to Infineon website "Packages"

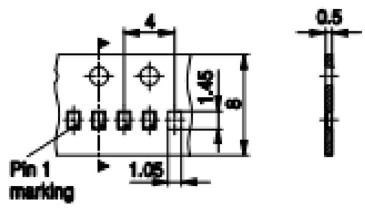


Marking Layout (Example)

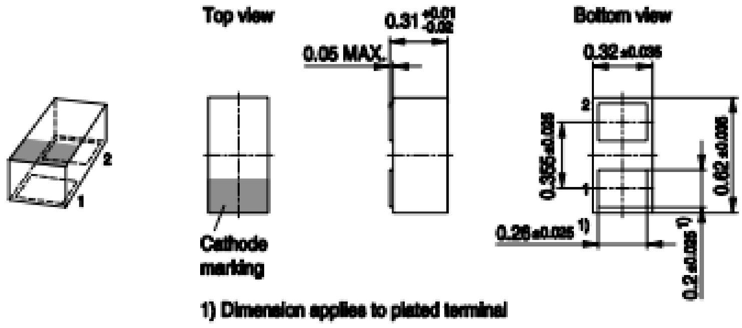


Standard Packing

Reel ø180 mm = 15.000 Pieces/Reel

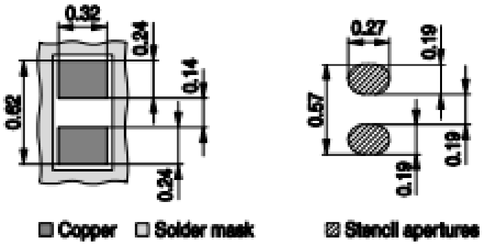


Package Outline

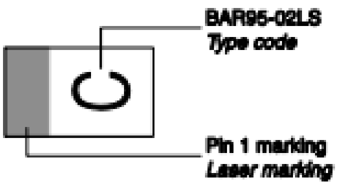


Foot Print

For board assembly information please refer to Infineon website "Packages"

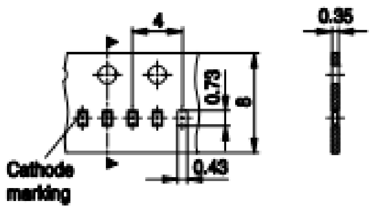


Marking Layout (Example)



Standard Packing

Reel ø180 mm = 15.000 Pieces/Reel



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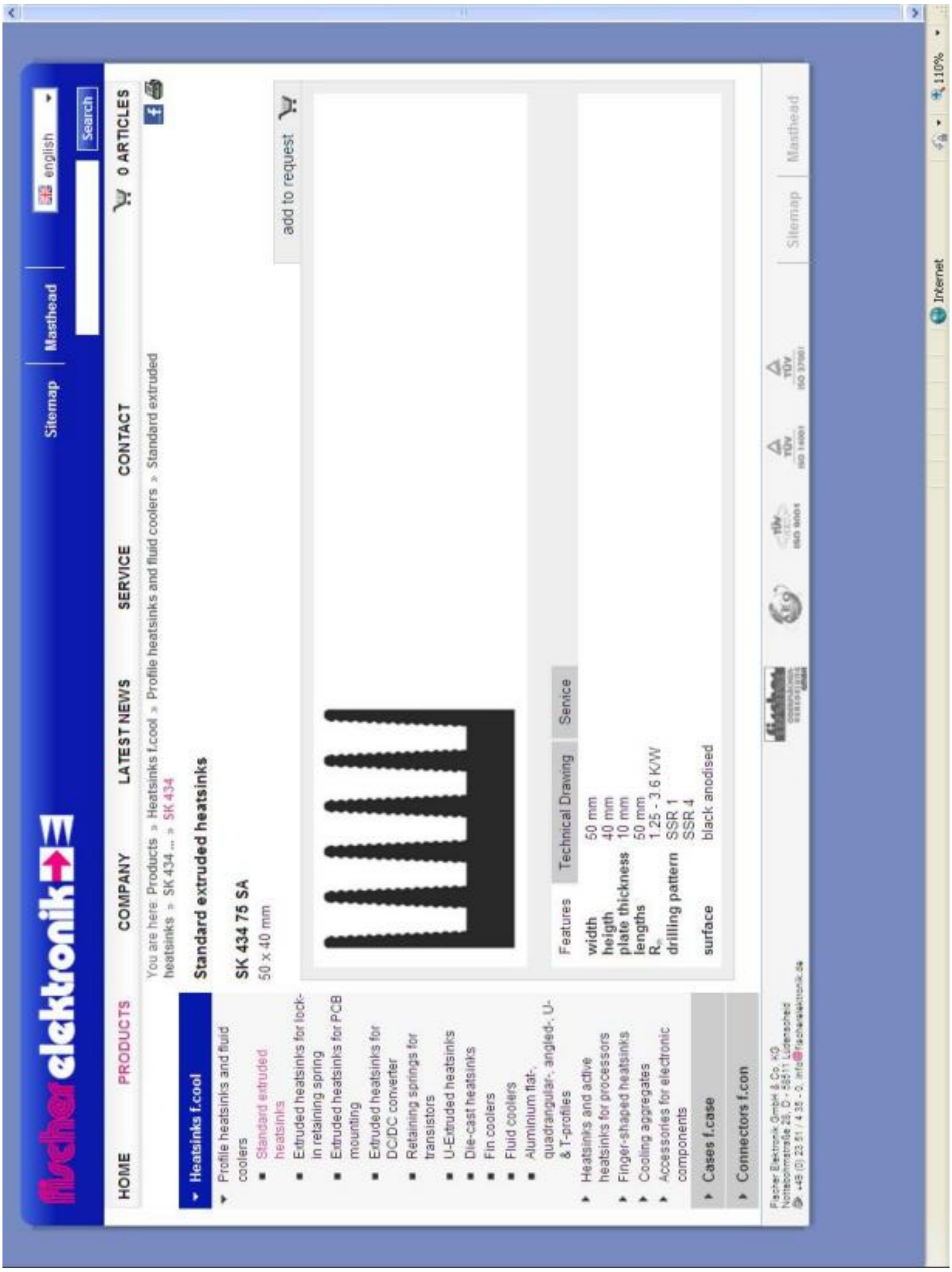
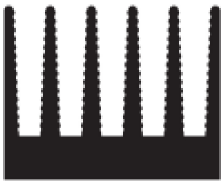
APPENDIX F: Technical Details for Fischer Electronik Heatsink



fischer elektronik
kühlen schützen verbinden

Data sheet Product SK 434 50 AL

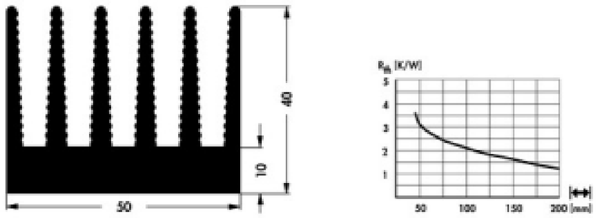


Profile heatsinks and liquid coolers>Standard extruded heatsinks
50 x 40 mm

Features

thermal resistance:	**3.6 - 1.25 K/W**
length:	**50 mm**
surface:	**raw degreased aluminium (by the metre raw aluminium)**
drilling pattern:	**SSR 1**
height:	**40 mm**
width:	**50 mm**
plate thickness:	**10 mm**

Technical Drawing



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APPENDIX G: Technical Details for Graphite Interface Material

RS PRO

Datasheet

ENGLISH

GRAPHITE INTERFACE MATERIAL

Features

Ultra high thermal conductivity
Easy to assemble

Applications

Electronic components: IC / CPU / MOS
LED / M/B / P/S / Heat Sink / LCD-TV / Notebook PC / PC / Telecom Device / Wireless Hub etc.
DDR II Module / DVD Applications / Hand-Set applications etc

ROHS

Property	T	T-1	P-1	Unit
Type	Graphite	Graphite + adhesive	Graphite + PET	-
Colour	Black	Black	Black	
Thermal Conducvity	X-Y,350	X-Y,350	X-Y,350	W/mK
	Z,13	Z,10	Z,8	W/mK
Flammability Rating	V-0	V-0	V-0	UL 94
Specific Gravity	1.3 - 1.5			g/cm3
Graphite Contained	99.5	99.5	99.5	%
Hardness	80	80	80	Shore A

ADHESIVE			
Item	Unit	Value	Test Method
180° peel strength	N/	≥6	GB/T2792-1998
Initial bonding strength	Kg/inch	≥8	GB/T2792-1998
Holding stick strength	h/1gk/	≥24	GB/T2792-1998
Temperature resistance	℃	-50--150	VIF-W1-Y6-Ⅱ
Thermal conductivity	W/MK	10	

Part No.	Description	Property
7943979	150x150x0.16mm, no adhesive	T
7943973	150x150x0.16mm, 1-side adhesive	T-1
7943982	150x150x0.50mm, no adhesive	T
7943985	150x150x0.50mm, 1-side adhesive	T-1
7943989	150x150x0.50mm, PET coated, no adhesive	P-1
7943998	150x150x0.80mm, no adhesive	T
7943991	150x150x0.80mm, 1-side adhesive	T-1
7943995	150x150x0.80mm, PET coated, no adhesive	P-1

APPENDIX H: Technical Details for Surface Mount Ceramic Capacitor

Radio Frequency & Microwave Ceramic Capacitors

HiQ-CBR Series, EIA 0402 Case Size, C0G Dielectric

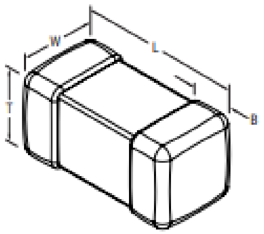
Electronic Components
KEMET
CHARGED.

Sample Kit Contents

KEMET Part Number	Case Size	Capacitance	Cap Tolerance	Rated Voltage	Dielectric	Quantity
	EIA/Metric	pF	%	VDC		
CBR04C108B1GAC	0402/1005	0.1	±0.1	100	C0G	100
CBR04C208B1GAC	0402/1005	0.2	±0.1	100	C0G	100
CBR04C308B1GAC	0402/1005	0.3	±0.1	100	C0G	100
CBR04C408B1GAC	0402/1005	0.4	±0.1	100	C0G	100
CBR04C508B1GAC	0402/1005	0.5	±0.1	100	C0G	100
CBR04C608B1GAC	0402/1005	0.6	±0.1	100	C0G	100
CBR04C708B1GAC	0402/1005	0.7	±0.1	100	C0G	100
CBR04C808B1GAC	0402/1005	0.8	±0.1	100	C0G	100
CBR04C908B1GAC	0402/1005	0.9	±0.1	100	C0G	100
CBR04C109B1GAC	0402/1005	1.0	±0.1	100	C0G	100
CBR04C129B1GAC	0402/1005	1.2	±0.1	100	C0G	100
CBR04C159B1GAC	0402/1005	1.5	±0.1	100	C0G	100
CBR04C189B1GAC	0402/1005	1.8	±0.1	100	C0G	100
CBR04C209B1GAC	0402/1005	2.0	±0.1	100	C0G	100
CBR04C229B1GAC	0402/1005	2.2	±0.1	100	C0G	100
CBR04C279B1GAC	0402/1005	2.7	±0.1	100	C0G	100
CBR04C309B1GAC	0402/1005	3.0	±0.1	100	C0G	100
CBR04C339B1GAC	0402/1005	3.3	±0.1	100	C0G	100
CBR04C399B1GAC	0402/1005	3.9	±0.1	100	C0G	100
CBR04C409B1GAC	0402/1005	4.0	±0.1	100	C0G	100
CBR04C479B1GAC	0402/1005	4.7	±0.1	100	C0G	100
CBR04C509C1GAC	0402/1005	5.0	±0.25	100	C0G	100
CBR04C569C1GAC	0402/1005	5.6	±0.25	100	C0G	100
CBR04C609C1GAC	0402/1005	6.0	±0.25	100	C0G	100
CBR04C689C1GAC	0402/1005	6.8	±0.25	100	C0G	100
CBR04C709C1GAC	0402/1005	7.0	±0.25	100	C0G	100
CBR04C809C1GAC	0402/1005	8.0	±0.25	100	C0G	100
CBR04C829C1GAC	0402/1005	8.2	±0.25	100	C0G	100
CBR04C909C1GAC	0402/1005	9.0	±0.25	100	C0G	100
CBR04C100J1GAC	0402/1005	10	±5	100	C0G	100
CBR04C120J1GAC	0402/1005	12	±5	100	C0G	100
CBR04C150J1GAC	0402/1005	15	±5	100	C0G	100
CBR04C180J1GAC	0402/1005	18	±5	100	C0G	100
CBR04C220J1GAC	0402/1005	22	±5	100	C0G	100
CBR04C270J1GAC	0402/1005	27	±5	100	C0G	100
CBR04C390J1GAC	0402/1005	39	±5	100	C0G	100
CBR04C470J1GAC	0402/1005	47	±5	100	C0G	100
CBR04C560J1GAC	0402/1005	56	±5	100	C0G	100
CBR04C680J3GAC	0402/1005	68	±5	25	C0G	100
CBR04C820J3GAC	0402/1005	82	±5	25	C0G	100
CBR04C101J3GAC	0402/1005	100	±5	25	C0G	100

One world. One KEMET

Dimensions – Millimeters (Inches)



Case Size (in.)	Case Size (mm)	L Length	W Width	T Thickness	B Bandwidth	Mounting Technique
0402	1005	1.00 ±0.05 (0.040 ±0.002)	0.50 ±0.05 (0.020 ±0.002)	0.50 ±0.05 (0.020 ±0.002)	0.25 +0.05/-0.10 (0.010 +0.002/-0.004)	Solder Reflow Only

www.kemet.com/CBR

APPENDIX I: Technical Details for Double Sided Copper Clad Boar

C.I.F

FR4 Data Sheet :-

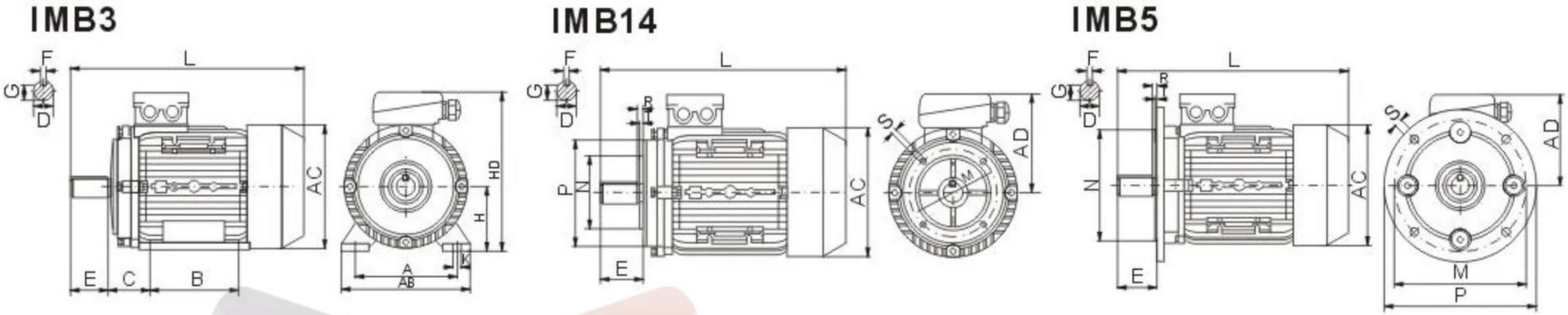
Test/Specification	FR4 Laminate Typical Values
Thermal Stress, Solder bath 288 deg. C	>60
Dimensional Stability, E-2/150	<0.04% Warp/fill
	<1.00% Bow/Twist
Flammability, Classification UL94	V0
Water Absorption E-1/105	0.10%
Peel Strength After Thermal Stress	11 lb./in After 10s/288 Deg. C
Flexural Strength	100,000 lbf/in^2 Lengthwise
	75,000 lbf/in^2 Crosswise
Resistivity After Damp Heat Volume	10 ^8 M ohms cm
Resistivity After Damp Heat Surface	10 ^8 M ohms
Dielectric Breakdown. Parallel to laminate	>60KV
Dielectric Constant @ 1MHz	4.7
Dissipation Factor @ 1MHz	0.014
Q-Resonance @ 1 MHz	>75
Q-Resonance @ 50 MHz	>95
Arc Resistance	125 s
Glass Transition Temperature	135 Deg. C
Temperature Index	130 Deg. C
A Few Other Relevant Facts from other Sources	
Specific Gravity	1.8-1.9
Rockwell Hardness (M scale)	110
Coefficient of Thermal Expansion	11 microns/m/Deg.C Lengthwise
	15 microns/m/Deg.C Crosswise
Thermal Conductivity	2.2-2.5 cal/h. cm Deg C

APPENDIX J: Technical Details for AC Motor

AMAS-R (Capacitor Run) : 2 & 4 Pole

Frame size	Rated output power	Rated current at	Full-load speed rpm	Full-load power factor	Full-load efficiency	Full-load torque	Starting current	Starting torque	Pull-out torque	Sound pressure level	Weight foot mounted
	P_N kW	230 V I_u A	n_N min^{-1}	cos φ	100% η %	M_N	(A)	M_S/M_N	M_K/M_N	dB(A) 1 metre (no load)	kg
AMAS-R 63K2	**0.18**	1.48	2800	0.92	60	0.063	5	0.40	1.7	70	3.9
AMAS-R 63G2	**0.25**	1.96	2800	0.92	63	0.087	7	0.40	1.7	70	4.4
AMAS-R 71K2	**0.37**	2.73	2800	0.92	67	0.129	10	0.35	1.7	75	6.2
AMAS-R 71G2	**0.55**	3.88	2800	0.92	70	0.195	15	0.35	1.7	75	6.5
AMAS-R 80K2	**0.75**	5.15	2800	0.92	72	0.258	20	0.33	1.7	75	8.3
AMAS-R 80G2	**1.10**	7.02	2800	0.95	75	0.366	30	0.33	1.7	78	11
AMAS-R 90S2	**1.50**	9.44	2800	0.95	76	0.513	45	0.3	1.7	83	15
AMAS-R 90L2	**2.20**	13.67	2800	0.95	77	0.752	65	0.3	1.7	83	17
AMAS-R 63K4	**0.12**	1.10	1400	0.92	55	0.087	3.5	0.4	1.7	65	4
AMAS-R 63G4	**0.18**	1.62	1400	0.92	56	0.127	5	0.4	1.7	65	4.7
AMAS-R 71K4	**0.25**	2.02	1400	0.92	61	0.175	7	0.35	1.7	65	6.3
AMAS-R 71G4	**0.37**	2.95	1400	0.92	62	0.260	10	0.35	1.7	70	7
AMAS-R 80K4	**0.55**	4.25	1400	0.92	64	0.375	15	0.35	1.7	70	9.5
AMAS-R 80G4	**0.75**	5.45	1400	0.92	68	0.511	20	0.32	1.7	70	11.6
AMAS-R 90S4	**1.10**	7.45	1400	0.95	71	0.758	30	0.32	1.7	73	14
AMAS-R 90L4	**1.50**	9.83	1400	0.95	73	1.029	45	0.3	1.7	78	17
AMAS-R 100L4	**2.20**	11.7	1400	0.98	83	1.513	56.7	0.3	1.9	86	23

AMAS-R (Capacitor Run) 1 Phase



Frame Size	Mounting dimensions (mm)																			Frame Dimensions (mm)					
										IMB14					IMB5										
	A	B	C	D	E	F	G	H	K	M	N	P	S	T	M	N	P	S	T	AB	BB	AC	AD	HD	L
63	100	80	40	11	23	4	8.5	63	7	75	60	90	M5	2.5	115	95	140	10	3.0	125	103	120	122	185	215
71	112	90	45	14	30	5	11	71	7	85	70	105	M6	2.5	130	110	160	10	3.5	138	113	140	135	205	245
80	125	100	50	19	40	6	15.5	80	10	100	80	120	M6	3	165	130	200	12	3.5	159	122	158	145	225	285
90S	140	100/125*	56	24	50	8	20	90	10	115	95	140	M8	3	165	130	200	12	3.5	175	155	175	150	240	330
90L	140	100/125*	56	24	50	8	20	90	10	115	95	140	M8	3	165	130	200	12	3.5	175	155	175	150	240	330
100L	160	140	63	28	60	8	24	100	215	130	110	160	M8	3.5	100	215	250	15	4	205	176	196	165	265	375