Organic electronics: benefits, barriers and opportunities

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NeuDrive works with its partners to develop the commercial applications of organic semiconductor materials and associated organic thin film transistor technology. NeuDrive's FlexOS™ inks and associated low temperature application processes have been developed to deliver outstanding transistor performance on flexible substrates. High charge mobility and the flexibility of the NeuDrive's transistor arrays can enable applications such ultra-thin wearable electronics, foldable displays and conformal biosensor devices.

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Executive Summary

In light of the continuing momentum behind the Circular Economy and Bio-economy agendas, organic electronics hold much promise in regards to future resource management. The materials used to create organic electronics could/can meet electrical product design requirements, replace the use of toxic materials, draw upon sustainable resources, upon disposal have the potential to offer regenerative properties back to the earth and at the same time support the strive towards a low carbon future. The report documents an exploratory research project on the introduction of organic electronics into the electronic and electrical equipment, funded by the Economic and Social Research Council Impact Acceleration Account. The research aims are highlighting 'violet biotechnology' (ethical, philosophical and legal), economic, environmental and societal themes that are seen as accompanying a shift from the existing electronics industry sector that utilises materials composed predominantly of inorganic materials. These topics might be perceived as benefits of the technology, barriers to its development, and implications for the sector and related areas, such as electronic waste. The grant supported a seven-month part-time project that examined the areas outlined, established links with industry partners, and undertook a literature analysis on the topic. The research objectives were intended to inform a future research-funding bid for a longer-term collaborative and interdisciplinary research project involving a variety of academic and industrial partners.

Key findings:

- Potential benefits of using organic electronics (OE, i.e. carbon-based electronics) relate to their flexibility and printability, using raw materials and processes that are less toxic and often requiring lower energy, and resulting in products that are 'greener' and more 'sustainable', potentially biodegradable and/or recyclable or disposable, cost-effective to make and complement the inorganic electronic markets (predominantly metal/silicon-based).

- The barriers to organic electronics relate to lack of an articulation for demand (and scalability), fragmented market (in Asia or USA), lack of infrastructural support, investment, restrictions/regulations, design (safety/toxicity, durability, efficiency and disposability).

- Unobtrusive biosensors for medical health applications (robotics and wearables), smart fabrics, smart packaging, toys and radio-frequency identification tags used in building key cards were identified as holding the most promise for future research (particularly due to its alignment with Industry 4.0 and intrinsic connection with the oncoming industry 5.0), more specifically addressing the following for each technology:
    - Legal – Policies and standards in driving development.
    - Ethics – who, how and what benefited from Organic Electronic developments
    - Philosophical – how knowledge claims are being made and what values and assumptions are being made in the process of development and use.
    - Environment – substitution for more bio-based materials; carbon life-cycle analysis; disposability and recyclability.
    - Economic – mapping the ecosystem of Organic Electronics and gathering perspectives; assessments of manufacturing and remanufacturing technologies; shared platforms for collaboration; consumer attitudes.
    - Social – Impact of Organic Electronics on society (e.g. accessible healthcare, future of work).

Whilst numerous themes have been identified, due to the size of the project our recommendations are to work with our collaborators to widen the participation in the project and narrow the scope to the organic electronics identified. With this in mind we would recommend:

- Widen participation in the pilot to ascertain other stakeholder's views on the findings and their insights into common challenges. Taking this step would ensure the areas identified hold promise for further development.

- Re-interrogate the research data, and broaden, to hone in on the organic electronic areas of interest (flexible biosensors & smart fabrics/labelling etc) in order to start to create an ecosystem mapping that includes material research (substitutability, toxicity, durability, disposability), the policy and standards landscape (Circular Economy; Bio-economy, IPR, design etc), the OE trajectories and value chain actors (that include material extraction, design, manufacture, use, disposability and recyclability), occupations attached with OE and organic electronic materials work, technologies used in manufacturing and disposal, markets and economies, media portrayals to gather insights into social acceptance and demand articulation.

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1. Rationale for this work

1.1 Background

Electronic technologies are ubiquitous in our everyday lives (touching every aspect of it from birth to death) and underpinning the industrial revolutions that support the economic success of countries across the world. Advances in the manufacturing and miniaturization of electronics (transistors, microprocessors, telecommunications, computers, etc.) during the 3rd industrial revolution enabled the 4th industrial revolution (particularly additive manufacturing, cyber physical systems and biotechnology) (Schwab 2016), which enables the 5th industrial revolution (mass customisation and personalisation). Different components of electronic technologies employ conductors and semiconductors to fulfil specific roles within the devices being manufactured, with organic conductors/semiconductors playing an increasingly important role in electronic devices (particularly useful in flexible displays, wearable electronics, etc.). Organic electronic materials (OEMs) are of interest for technical and biomedical applications. OEMs are typically comprised of fullerenes (e.g. spherical bucky balls or ellipsoidal/tubular nanotubes), graphene/graphene oxide, or conjugated polymers (e.g. derivatives of polyaniline, polypyrrole or polythiophene [particularly poly-3,4-ethylenedioxythiophene, PEDOT]).

OEMs display interesting optoelectronic properties, and respond to electricity, light and magnetism in a structure-dependent fashion, and are produced via a variety of chemical methodologies (e.g. solution/vapour phase synthesis) on a vast scale, however, their green synthesis from renewable resources has not yet been explored fully. The intention of this research was to explore research opportunities that support the use of various biotechnological approaches to produce OEMs from renewable resources for optoelectronic applications. The 53.6 million tonnes of electronic waste being discarded, and growth of ca. 2 million tonnes a year, worth an estimated 57 billion USD in raw materials alone gives an indication of scale and possibility (Forti et al., 2020). According to the World Bank over 2 million informal sector workers are employed in waste and the waste sector is argued to be the third largest employer worldwide (ILO 2018). The shift to biotechnological approaches of materials production (e.g. synthetic/engineering biology) has significant implications to those operating in the reuse and recycling sector. Future research projects have the potential to have significant positive impacts in the following areas:

- Economic impacts by generating new chemicals/materials and intellectual property for a multibillion £GBP industry, estimates of 45 billion dollars are given to produce current electronics per annum (Baldé et al. 2017) and market growth of Organic Electronics (OE) is forecast to reach a market share of approx. 12 billion dollars (Mühl and Beyer, 2014: 61).
- Environmental impacts by adoption of renewable resources and green processes and diminishing the amount of e-waste (ca. 50 M tons) generated annually (Forti et al., 2020).
- Social impacts in regard to occupations (new, transitioning and current), and health impacts by the use of technologies for medical applications.

Funding was obtained from the Economic and Social Research Council (ESRC) Impact Acceleration Account fund, to conduct exploratory research on OE for use in the electrical and electronic equipment sector. The research aimed at highlighting ‘violet biotechnology’ (legal, ethical and philosophical), environmental, economic and societal issues that are seen as potentially accompanying a shift from the traditional manufacturing methods used in the existing inorganic electronics sector. These might be perceived benefits of the technology, barriers to its development, and implications for the sector and related areas, such as e-waste. With this in mind, the key objectives are as follows:

- Engage with industrial stakeholders operating in the UK & overseas.
- Develop an overview of the potential impacts and important questions in need of further/deep study (desk-based research and meetings with partners).
- Develop a report documenting the project and findings that can be used to inform the development of the planned interdisciplinary grant application.

This report documents a part-time seven-month exploratory research project between September 2019 to March 2020 and the findings. The report aims to generate discussions between academic and industrial partners on the potential for longer-term collaborative and interdisciplinary research projects.

2.0 Definitions and demarcation of violet biotechnology and organic electronics

"Biotechnology" [is]… any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use" (UN 1992: 3), and is a relatively new interdisciplinary scientific field. Biotechnologies are categorised by colours of the rainbow to differentiate the different activities, for example, red for medical and health, yellow for food through to grey for fermentation - see figure 1 below (DaSilva 2012). The violet category emerged in June 16th, 1980 after a "US Supreme Court came to a decision that genetically modified microorganism can be patented" (Kafarski 2012: 815). This new categorisation refers to legal, ethical and philosophical issues in an attempt to ensure biotechnology development is undertaken in the right manner and to act as a platform for discussion, more specifically in the realm of regulation, patents and intellectual property (*ibid.*).

Color Type	Area of Biotech Activities
Red	Health, Medical, Diagnostics
Yellow	Food Biotechnology, Nutrition Science
Blue	Aquaculture, Coastal and Marine Biotech
Green	Agricultural, Environmental Biotechnology – Biofuels, Biofertilizers, Bioremediation, Geomicrobiology
Brown	Arid Zone and Desert Biotechnology
Dark	Bioterrorism, Biowarfare, Biocrimes, Anticrop warfare
Purple	Patents, Publications, Inventions, IPRs
White	Gene-based Bioindustries
Gold	Bioinformatics, Nanobiotechnology
Grey	Classical Fermentation and Bioprocess Technology

Figure 4. Typology of the Electronic Journal of Biotechnology
Source: http://www.ejbiotechnology.info/index.php/ejbiotechnology/article/view/1114/1496

Figure 1: Typology of the Electronic Journal of Biotechnology, DaSilva (2004)

Before this categorisation, countries including the US and Germany gave private companies Intellectual Property Rights (IPR) rights over plant varieties. In response, 10 European countries reacted to similar calls from countries by coming together to create a convention, the International Union for Protection of New Varieties of Plants (UPOV), which was signed in 1961. The Organization for Economic Cooperation and Development (OECD) and the World Intellectual Property Organization (WIPO: a permanent UN body responsible for international cooperation in intellectual property) have conducted studies into IPR issues around biotechnology. The findings of their reports are used as a framework for IPR legislation on biotech by different countries, resulting in criteria used to assess applications for patent rights in biotechnology. In the US there are 5 such criteria: matter eligibility, novelty, utility, non-obviousness, and no previous disclosure. In Europe, three criteria apply: "it must be new, industrially applicable and involve an inventive step." (Gold, Herder and Trometter 2007). However, the violet category has come under criticism as an ill-fitting classification as legal, ethical and philosophical issues span all categories and should be kept in mind for all developments (Matyushenko et al. 2016).

Organic electronics (OE) are a platform technology that use carbon-based materials such as polymers or small molecules to transmit electricity (as detailed above). These technologies enable numerous applications and vary considerably in their specification. One of the connections to biotechnology is that carbon, replicates molecules of living things (Heiber, Wagenpfahl and Deibel 2019) – their application could fall into numerous categories such as Red for health applications with biosensors or wearable technologies or yellow/gold/white with smart labelling using RFID technology. The findings indicated the preference for alternative terms, such as:

- Organic Large Area Electronics (OLAE)
- Flexible Electronics
- Thin-film, Organic and Large Area Electronics (TOLAE)

Within these (flexible) categories the results spanned the OE components, OEMS and the products they are used in, see table 1 below:

Building blocks for OE	Components of OE products	Products OE's are used in
Solvents – green & toxic Substrates – polymers (natural biopolymers including polysaccharides such as cellulose/starch, and proteins such as silk/wool, or synthetic polymers such as polyethyleneterephthalate [PET]) typically coated with a conductor such as gold or indium tin oxide [ITO] Printing inks (incorporating solvents, polymers, and particulates)	Organic thin-film transistors – OTFT Organic light emitting diodes – OLEDS Organic photovoltaic – OPV	Televisions, computer monitors, portable systems, smart phones, wearable technologies (smart watches)
	Biosensors (medical applications) Organic light emitting diodes – OLEDS Organic photovoltaic panels	Integrated smart systems - disposable diagnostics (robotics), smart lighting, smart fabrics, interactive packaging (labelling RFID), building key cards (RFID), large area sensors (e.g. roofing with photovoltaic panels).
	Organic thin-film transistors – OTFT	Electrodes and semi-conductors

Low and high molecular weight conjugated species (fullerenes [Bucky balls, carbon nanotubes], graphene derivatives, polymers (polypyrrole, poly(3,4-ethylenedioxythiophene) [PEDOT]), Spiro(fluorene-9,9'-xanthene), pentacene, rubrene).	Organic light emitting diodes – OLEDS Organic photovoltaic – OPV Organic Semiconductors Organic field-effect transistors (OFET)	

Table 1: OE components, OEMs and products

In addition, OE components and OEMs highlighted that these were not specifically tied to biotechnology as the materials used and integration into electronic and electrical products put the OE as hybrids of organic and inorganic material. Some substrates are made up of plastics, solvents are used, and some printed circuits contained non-renewable resources (e.g. indium, silver, gold and copper etc.). The results detailed below, is an attempt to take these additional factors into account and document the output from the desk-based, interviews and survey analysis of the benefits, barriers and future optoelectronic research opportunities.

3.0 Benefits of OE

Manufacture and market opportunities, material substitution and energy, flexibility, printability and health framed the key benefits of OE components. Manufacture and market opportunities related to cost-efficiency attached to manufacture, and market opportunities to complement the existing silicon-based electricals sector and enter the health industry. Material substitution themes were attached with the use of less toxic materials and low energy requirements resulting in products that are 'greener' and more 'sustainable', often biodegradable and/or recyclable or disposable. Flexibility and printability were attached with technical design and health benefits came from the use of applications.

3.1 Manufacturing

Manufacturing OE has significant cost benefits attached due to the ability to reduce production costs when achieved at scale in comparison to manufacturing Complementary Metal-Oxide Semiconductors (CMOS). Reasons identified ranged from a reduction in vacuum processing temperature (OE 115 vs. CMOS 1000), thereby reducing energy consumption, lower cost materials, roll-to-roll fabrication methods to print/coat/laminate or embed material onto substrates (CS3 2012; COLAE 2013; OLAE 2009; Strassen et al. 2017).

3.2 Market and competition

With OE being lightweight, small and flexible, low power (OLAE 2009) and easy to integrate allows the products to compliment current silicon-based markets in display technologies and target 'promising markets' in health industry applications (sensors) and devices. Consumers typically do not realise the need for special recycling such as Radio Frequency Identification (RFID) (e.g. building key cards/smart labelling), electronic toys, remote controllers and smart watches (Chang et al. 2017).

Comparisons between organic and inorganic electronics emerged and identified OE as a "parallel technology" in a "parallel market" rather than in direct competition with the traditional silicon-based industry. Whilst traditional silicon-based electronics were seen as "high specification" and OE as "low specification", this was not seen as disadvantageous per se, rather, it was suggested that the lower specification of OE was suitable/preferable for the identified/intended products (display technologies and (bio)sensors) and their anticipated lifespans. Currently OE cannot substitute silicon (polysilicon) due to fundamental differences in their electronic properties. Products that are functional using components with lower conductivity than metals/silicon/CMOS (e.g. OTFT displays like watches or biosensors used in medical robotic applications) are therefore not perceived to be in competition with silicon.

3.3 Low energy and material substitution

As mentioned above, the vacuum process in manufacturing requires less energy to make and the OEs having a lower performance specification consumes less energy during use, more specifically this related to OTFTs and OLEDs (CS3 2012; OLAE 2009). However, there is an overarching material benefit related to substitution of non-degradable materials with biodegradable materials derived from abundant natural feedstocks (Lovley 2017). Specific examples given are detailed below:

- Replacement of non-degradable plastic substrates with starch paper substrates that are degraded by fungi (Jeong et al. 2017), polypropylene carbonate (OFTFs) that are degraded by lipase (e.g. from *Rhizhopus oryzae*) (Rullyani et al. 2018); cellulose (Martins et al. 2011; Najafabadi et al. 2014); chitin, silks, gelatin, shellac, collagen, and cellulose-based polymers (Rullyani et al. 2018).

- Printing inks made from egg white, carbon or soot (Le Borgne et al. 2019).

- Aqueous processing to replace solvent use during the production of OPVs (Zhang et al. 2016).

- Graphene replacing indium tin oxide (limited resource) (Akin, I., et al. 2014; Alvial-Palavicino and Konrad 2019).

- Biomass and an aqueous fabrication process for organic semiconductors (Sun et al. 2015).

Through the material replacements the OE components and some processes were perceived to be more sustainable, and, in some cases, biodegradable, recyclable and or disposable.

3.4 Flexibility and printability

A key benefit of OEs is the physical flexibility these components offer due to the ability to print them, indicating the ability to produce on scale as documented above. Illustrations were given regarding OPVs (Dos Reis Benatto et al. 2014; Lui et al. 2014), integration into roofing (OLAE 2009) and office windows, the use in bioelectronics for medical applications, and novel products such as lighting, smart fabrics advertising billboards, newspapers, magazines, signs labels, RFID tags (Agate et al. 2018; Liu et al. 2014; Martin et al. 2013), smart phones (Amasawa et al. 2016).

3.5 Health benefits – personalised biomedicine or bioelectronics

OE's, more specifically, biosensors and display technologies offer the opportunity to address grand societal challenges in medical health and healthcare. Due to lower production costs and the use of less harmful or biobased materials these products could make affordable diagnosis and treatment to a wider demographic of the world population. For instance, implantable electronic interfaces that allow controlled drug delivery, wearable devices to monitor wellness and healthcare for aging population (OLAE 2009; Mühl and Beyer 2014; Liao et al. 2015).

4.0 What are the barriers to OE?

With the derived benefits of OE's being flexible, printable, complimentary to current silicon-based markets, cheaper to make, less toxicity due to biobased material substitutions and manufacturing processes, the question arises as to why some of these technologies and materials were not more ubiquitous? The combined desk-based research, interviews and survey results indicated the need for a holistic understanding of the product design and performance implications, a need for a more common shared language and reassessment of business models for commercialisation and manufacturing processes.

More specifically, the findings signposted the need to examine the following areas in more detail:

4.1 Product design and performance:

- Product design models (innovation) did not always take into account the full lifecycle, regarding molecule/material sourcing, disposability and recycling (leaching of metals (Epinosa et al. 2015); RoHS or WEEE legislation; material reclamation), specifically in regard to RFID usage in smart labelling or office entry keys, biosensor applications, or OLEDS.

- Substitutability for biodegradable materials (in substrates, solvents, inks and electrodes (Jeong et al. 2017; Rullyani et al. 2018; Tobjörk and Österbacka 2011; Zhang et al. 2016). The use of both biobased and non-biobased substances creates hybrid products that have non-biodegradable features e.g. paper or polypropylene substrates with circuits printed for OLEDs or OPV; fluorinated solvents used in the fabrication process or some printing inks.

- Durability, stability and operating lifespan of OLEDs and OPVs was poorly understood (e.g. more efficient light can generate more energy consumption (Lizin et al. 2012)), there is a need for a life cycle analysis that takes into account the whole system, device and the component parts (Lupo 2014) – especially when it relates to product performance.

- OEMs need to be designed to take into account their integration into different devices.

4.2 Shared and common language:

Standardisation of language as currently violet biotechnology appears an inappropriate term to use when exploring OEM/OE because current manufacture processes do not capitalise on the potential of synthetic/engineering biology (i.e. white biotechnology) and OEM/OE are compared with silicon-based electronics. Definitions and demarcation of OE is varied, and preferred terms were 'Large Area Electronics', 'Flexible Electronics', and 'Thin-film, organic and large area electronics' (TOLAE).

4.3 Commercialisation and Manufacturing:

- Commercialisation and competition in EU, current insights indicate a lack of an articulation for demand for OEs and OEMS (consumers/regulators), fragmented markets (e.g. currently in Asia and USA (NRC 2014)) and competition (e.g. Television and Display producers dominate OTFT markets).

- Scalability, investigations into areas related to available infrastructures (e.g. silicon dominate production), reproducibility (uniformity as has been seen with OLED based smartphones), and investment (e.g. not getting out of pilot phase).

- Manufacturing process for OEs and a comparison between the embodied energy versus energy usage and disposal.

- Sourcing bio-based materials and molecules and implications for large scale production.

- The role of regulators and legislation. The findings indicated three legal implications patents (IPR), waste of electrical and electronic equipment legislation and the restriction of hazardous waste legislation, no other laws or standards were mentioned.

5.0 Observations on OE and OEMs

From this small-scale pilot study, the following observations can be made in regard to the legal, ethical, philosophical, environmental, economic and societal considerations. It should be noted that whilst they are documented under specific headings, some observations would span more than one category, as they are interlinked.

5.1 Legal

The survey and interview results indicated restrictive legislative concerns regarding the ability to test new OEMs and OE components within the UK and EU – indicating Asia and the USA as product and component development destinations, although exactly what these restrictions are were not ascertained. While the research papers indicated challenges around IPR (e.g. what can and cannot be included in a new patent), the other legal implications related more to product design and end of life, more specifically the Restriction of Hazardous Substances and Waste, and Waste of Electrical and Electronic Equipment Directives – specifically in the areas of display technologies, biosensors and novelty application usage (e.g. smart packaging and RFID building entry cards). It is acknowledged that this area was not pursued in research journals, industry papers or practitioner journals related to law – this could explain the absence.

In addition to the legal frameworks some standards were also indicated such as ISO 10993 in regard to testing and evaluating biocompatibility. However, as noted above, one key finding related to lack of a shared common language or actors operating in this area.

Research Recommendations: Two research projects that map out the UK and EU policy and standards ecosystem for 1) biosensors (wearable technologies) and 2) novelty application usage (smart fabrics, packaging and RFID key cards), taking into account the full life cycle and then compared with Asia and USA landscapes. The aim of the projects would be to identify common language, and insights in the perceived restrictions and opportunities surrounding product, policy and standard development in the UK and EU.

5.2 Ethical

The ethical concerns centred around the use of OE components and OEMs in medical health applications and their potential use, as well as issues around policy and the recreation of specific value systems attached with certain resources. For the medical application the concerns related to the differences between unobtrusive use - such biosensors in wearable technologies to monitor ongoing physiological and medical health issues such as depression, drug addiction etc. (Bansal et al. 2018) and obtrusive uses that were created in laboratories and implanted to recreate electronic signals for the nervous systems (e.g. treating Parkinson's for instance) (Horsch et al. 2008). In addition there were concerns regarding equity and medical health applications. Regarding the valuation of specific resources, policy was at the centre of these discussions, although not always attached with OEMs and OEs (Gregson et al. 2015).

Discussions relating to the sourcing of natural materials and impact this could have on biodiversity and nature for all OEMs and OEs was lacking. In addition, there was limited insights into unintended consequences with the introduction of the technology e.g. collecting data on specific patients and impacts that might have on insurance, monitoring health in the workplace, or if the technology failed, as well as limited consideration for those working in the informal waste sectors and potential implication these developments may have on their future of work. Finally, the subject of clinical trials on animals for obtrusive OE and OEM use was also not addressed fully in the research data.

Research Recommendations: The following research projects to explore who, how and what benefits come from the use of OEMs and OEs should be undertaken:

- The ethics of unobtrusive biosensor use in robotics and wearable technologies and/or novelty smart applications.
- The ethics of sourcing ecosystem services for material substitutions in OE's focusing on inks, substrates and solvents.

The aim of these projects would be to examine and gather insights into the potential impacts within different societal contexts and what considerations are and/or could be made to enhance the development or future development of these technologies – specifically in regard to equity and driving an inclusive, restorative and regenerative economy and society.

5.3 Philosophical

It was noticeable in the absence of philosophical debates in relation to OEMs and OE in the research results.

Research Recommendations: Revisit the current research data to explore of whether OEM and OEs are appropriate developments and to examine and extract insights into methods used in their development, how knowledge claims are made and what values and assumptions are being made. The aim of this research would be to enrich insights into taken for granted moral values and logics that are used in judgements and decisions surrounding the development of OEs and OEMs.

5.4 Environmental

Most of the environment considerations focused on the material and molecular substitutability or energy reductions in the manufacturing process. In regard to material or molecular substitutability the results indicated that areas that held most promise related to the replacement of harmful components in substrates, finding solutions to the development of bio-friendly solvents and printable inks. Whilst OE technologies and OEM materials hold significant promises for the optoelectrical industries our findings indicated that further consideration needed to be given to the full life cycle of the technology, product development and distribution, usage and end of life. The components and materials covered in the remit of this research often did not look at the end product as a whole and were often hybrids of organic and inorganic materials. Moreover, there were limited insights into the energy used in the full supply and/or value chain involved in the production, consumption and end of life practices. It was extremely noticeable that end of life practices had yet to be fully considered both in the design of the product through to the recycling – that could be attributed to not enough of the OE components or electronics appearing in recycling streams, lack of awareness in regards to the product contents and required pathway, and/or the potential cost currently attached with extracting materials of value e.g. costing more to extract than produce.

Research Recommendations: There are numerous material, environment and management science projects that could be undertaken here.

- Material Science – Substitutability with biobased materials to address concerns regarding sensitivity to moisture, durability and disposability of products. Specific areas of focus to include greener solvents, semiconductors, substrates and inks.
- Environmental Science – Lifecycle analysis of the carbon footprint of OEs (specifically biosensors and smart devices) and the embodied energy used to produce the product.
- Management (Social) Science – Disposability and recycling policies and practices with current OEs (specifically display, biosensors and smart products (fabric/packaging/RFID key cards)).

The aims of these projects are to gather insights into resource management, understand best practices, and reduce environmental impacts and support the low carbon economy.

5.5 Economic

The results indicated numerous benefits and opportunities for OEMs and OEs to become more ubiquitous, integrated in more products and complimentary to current Silicon based markets. With the TV and display markets appearing to be saturated, the results indicated gaps in regard to the biosensors for use in unobtrusive medical health applications and novelty products such as smart fabrics, smart packaging or RFID key cards. What was evident was a more in-depth understanding is required of the ecosystem in which these products are developed, marketed, sold and used.

Research Recommendations: There are four research agendas that could be followed:

- Ecosystem mapping for OEs that encapsulates both market and non-market actors, and their perspectives of the market in order to understand articulation of demand and market bases.
- Circular/bio-based business models and their use in OE production.
- Assessment of manufacturing and remanufacturing technologies to map out the OE infrastructure and further opportunities for scalability.
- Collaboration to create a common platform for people to share expertise, e.g. circuit board example (design sent to the silicon foundries who make it).
- Consumer attitudes to OEM and OEs and the throwaway society.

Gathering such insights could give an indication of the types of business models used, where the product demand is, how demands are articulated by various stakeholders throughout the value chains and markets, and the connections with the low carbon circular and bioeconomy agendas. These findings could support industry and policy makers agendas in regard to investment areas.

5.6 Social

The benefits to society did not feature in any depth in the findings. The main articulation related to the potential advances in healthcare and medical applications that OEM and OE's could offer. A cursory nod was made towards the contribution to reducing environment impacts in comparison to the more pervasive methods of producing electronic and electrical equipment.

Research Recommendations: Further research is required into the following areas:

- How OEM and OEs currently impact upon society and future potential?
- What type of occupations are attached with OEM and OE developments? What are the implications for the future of work (old/new/revised) – especially if markets are overseas and spill into formal and informal economies.

These findings could support industry and policy makers agendas in regard to areas of investment in areas of low carbon economy expansion, attracting future talent and training requirements.

6.0 Next steps and future research opportunities:

The output from the research indicated that the OE components that appeared to hold the most promise for future research, and of interest to the interviewees and survey respondents, related to developments in the production of unobtrusive biosensors for medical health applications (robotics or wearables) and OEs integrated into fabrics, packaging, toys, and use of RFID chips. It also came about that there was an increasing importance for the research to be transdisciplinary so a holistic understanding could be ascertained. For example, material scientists working on bio and eco-friendly substitutions in OEs; industry partners and management scientists to explore supply and value chain implications as well as macro and micro level transactions; law researchers and policy influencers to gather insights into legalisation and standards, and environmental scientists to gather insights into carbon footprints etc.

With that above in mind we would propose the following next steps to continue momentum and develop future research opportunities.

- Widen participation in the pilot to ascertain other stakeholders' views on the findings and their insights into common challenges. Taking this step would ensure the areas identified hold promise for further development.

- Re-interrogate the research data, and broaden, to hone in on the OE areas of interest (flexible biosensors & smart fabrics/labelling etc) in order to start to create an ecosystem mapping that includes material research (substitutability, toxicity durability, disposability), the policy and standards landscape (Circular Economy; Bio-economy, IPR, design etc), the OE trajectories and value chain actors (that include material extraction, design, manufacture, use, disposability and recyclability), occupations attached with OEM and OE work, technologies used in manufacturing and disposal, markets and economies, media portrayals to gather insights into social acceptance and demand articulation.

Taking the outlined steps would provide a firmer basis to formulate a research proposition that addressed the data gaps, barriers and observations documented above. In addition, these insights would help ascertain priorities as to the order in which these activities are tackled (either at the same time or separately).

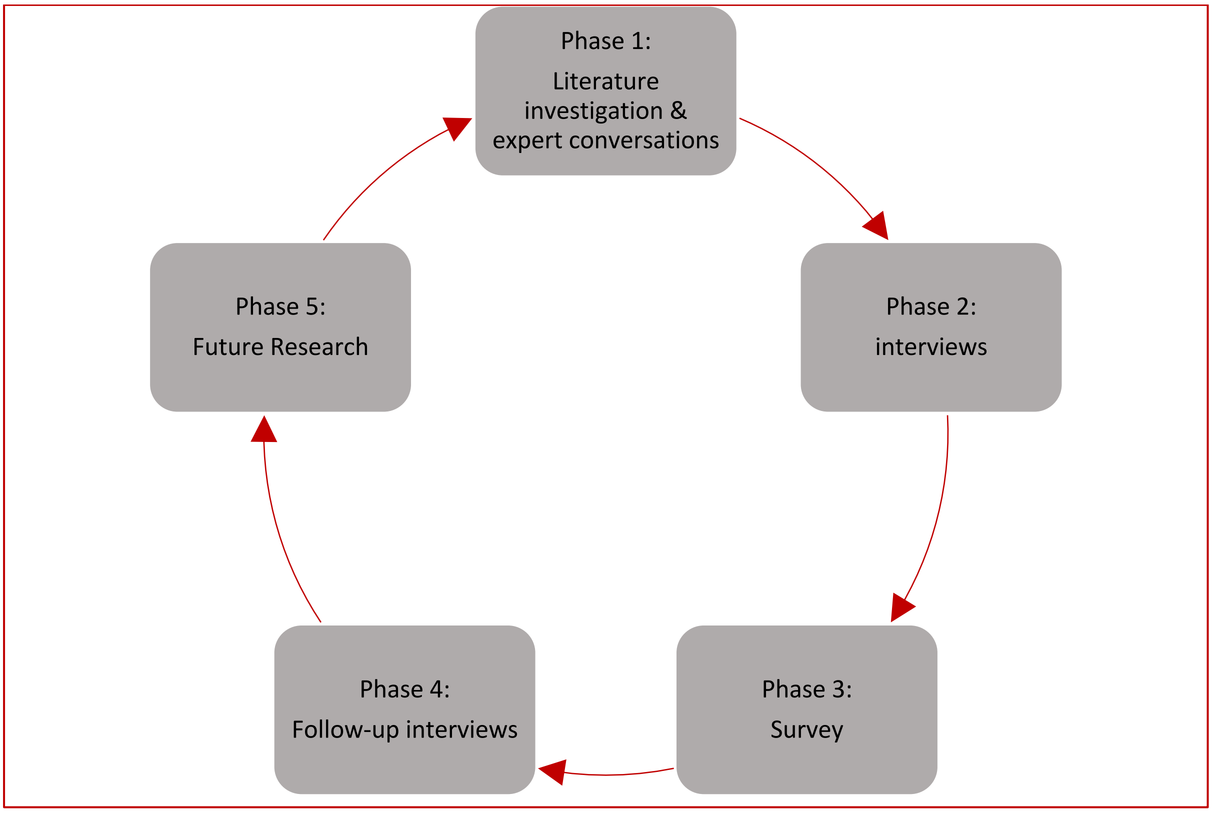
Annex 1 Methodology, scope and project phases

A qualitative part-time exploratory desk-based approach was adopted. The work was carried out over a 7-month period between September 2019 and March 2020, involving:

- 350 papers reviewed (academic research papers, white and grey literature and reports).
- 6 expert interviews conducted (OE producer, Asset Recovery Company, Recycler and 3 material science experts).
- 84 individuals surveyed (37 responses).

The scope of the project was limited to display technologies and had the following three objectives:

- Engage with industrial stakeholders operating in the UK & overseas.
- Develop an overview of the potential impacts and important questions in need of further/deep study (desk-based research and meetings with partners).
- Develop a report documenting the project and findings that can be used to inform the development of the planned interdisciplinary grant application.



Phase 1 – Desk-based literature review and expert conversations was the initial and main research activity, in terms of time resource. The literature review began with investigating 'violet biotechnology' and how it might apply to Organic Electronics (OE) and proceeded in an inductive manner. Key search terms were used to search the literature using Google Scholar and, where necessary, Lancaster University's own OneSearch facility to locate literature, initially from the most recent years. This helps to identify meta-reviews of topics, and to obtain a snapshot of the sector under research, at the current time. The inductive approach meant that the most salient issues (and those missing in the literature) were identified first, and the key themes for analysis could be summarised. Later stages of the literature search and review then proceeded to seek for more specific literature on these issues. In addition, two material science experts were contacted and provided additional material.

Phase 2 – Expert interviews were held between October and November 2019**.** The interviews were semi-structured and reflected on the key literature review findings, but were also fairly open-ended and naturalistic, reflecting the exploratory nature of the research. To broaden the research and triangulate some of the findings, **Phase 3 - Survey of Organic Electronic sector opinion** was undertaken. The survey questions were based upon the literature review findings and canvassed people with questions about the perceived benefits of, and barriers to, the development of the OE market, particularly in the UK. The survey was initially distributed through LinkedIn, based on keyword searches, and respondents were invited to further distribute the survey link. A small sample of willing interviewees were identified and contacted to follow up on and elaborate their responses **(Phase 4).** The sample was initially focussed on UK individuals and then extended internationally. There is no claim to statistical validity for the sampling or the findings, which were intended to act simply as a confirmation of the findings in the other parts of the research.

Levels of confidence and limitations:
During the course of the research project the chosen data analysis software corrupted and the product manufacturers were unable to fix this in a timely fashion. Whilst most of the research had been completed, some analysis has been lost and other areas would need to be re-interrogated to ensure accuracy. Confidence levels are medium because of the data corruption, the depth of the survey and the low number of expert interviews.

Annex 2 Glossary

Aqueous processing is using water as a solvent.

Biocompatibility refers to the ability of some material to undertake the desired function and not cause a reaction or impact to the recipient. The term is often associated with implanted medical devices/materials.

Biomass is organic material derived from animals and/or plants, and a source of renewable energy.

Biosensors are technologies that analyse biological systems by converting biological responses into optical/electrical signals.

Biotechnology "means any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use "(UN 1992; 3).

Cellulose is a linear polysaccharide composed of β(1→4) linked D-glucose units, and the most abundant biopolymer on earth.

Chitin is a linear polysaccharide composed of N-acetylglucosamine.

Collagen is the most abundant structural protein in the extracellular matrix of mammals.

Electrodes are conductors through which electricity enters or leaves an object, substance, or region. Anodes (-) are defined as electrodes where electrons leave the electrode/circuit and oxidation occurs, and cathodes (+) are electrodes where electrons enter the electrode/circuit and reduction occurs.

Fluorinated chemicals contain the element fluorine (F).

Graphene is a form of carbon consisting of one atom thick planar sheets.

Inorganic materials are not organic (i.e. carbon-based compounds).

Lipases are enzymes that can catalyse hydrolysis of esters, interesterification, transesterification, acyl transfer to other nucelophiles. Phosopholipases are a class of lipases that can catalyse hydrolysis of phosholipids.

Metal oxides are composed of an appropriate ratio of metals and oxygen (which tends to be in the -2 oxidation state) to have a net neutral charge.

Organic matter is carbon-based.

Organic bioelectronics are devices engineered from electrically conductive carbon-based substances (e.g. derivatives of fullerenes, graphene, nanotubes/nanohorns, etc.) and typically used for medical/environmental applications.

Organic light-emitting diodes (OLEDs) are light-emitting diodes (LEDs) in which the emissive electroluminescent layer is composed of an organic compound that emits light in response to an electric current.

Organic Electronics (OE) are a platform technology that use organic substances as components of electronics.

Organic Electronic Materials (OEMs) are typically comprised of fullerenes (e.g. spherical bucky balls or ellipsoidal/tubular nanotubes), graphene/graphene oxide, or conjugated polymers (e.g. polyaniline, polypyrrole or polythiophene).

Organic Photovoltaics (OPVs) use organic electronics for light absorption and/or charge transport enabling the production of electricity from light by the photovoltaic effect.

Organic Thin Film Transistors (OTFT) – "technology involves the use of organic semiconducting compounds in electronic components, notably computer displays. Such displays are bright, the colours are vivid, they provide fast response times, and they are easy to read in most ambient lighting environments." (Rouse, 2020; para. 1)

Polymers are molecules composed of large numbers of similar units (e.g. monomers/oligomers) attached (bonded) together.

Polypyrrole (PPy) is a polymer composed of large numbers of pyrrole monomers attached to one another.

Polysilicon (or multicrystalline silicon) is a high purity, polycrystalline form of silicon, that is used as a raw material by the solar photovoltaic and electronics industry.

Rhizhopus oryzae is a species of fungus.

Roll-to-roll processing is a fabrication method used to coat, embed, laminate or print substances onto a flexible rolled substrate material (fed continuously from one roller on to another) used in the manufacture of large area electronics.

Radio-frequency identification (RFID) is a technology that has data pre-set, typically on labels or tags that enables a reader to capture the data via radio waves.

Semiconductors are substance with conductivity between insulators and most metals (typically due to the presence of an impurity or temperature effects).

Shellacs are melted lac resins used to coat other substances (e.g. nail varnish).

Smart fabrics are fabrics that contain an RFID tag.

Smart labels are materials (e.g. paper/plastic/or other) that contain an RFID tag.

Solvents are chemicals able to dissolve other chemicals.

Spiro(fluorene-9,9'xanthene) is the chemical with CAS Number: 1887794-22-0.

Substrates refer to a film/layer or substance used on which an enzyme/electronic current acts.

Vacuum processing refers to methods using vacuums.

Violet biotechnology category refers to legal, ethical and philosophical issues of biotechnologies.

Wearables are "technologies that connects to individuals in some capacity, examples include Fitbit, I-I-watches etc.

Annex 3 - References

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