The IoT and the Environment: A Paradigm Shift in Sustainable Development

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In 2015 former Google CEO, Eric Schmidt, said "The internet will disappear. Imagine you walk into a room, and the room is dynamic…you are interacting with the things going on in the room" (Smith). Schmidt was referring to the rise of the Internet of Things (IoT), a technology space encompassing all network-connected objects from fitness trackers to smart home sensors. Over the last twenty years, the number of IoT devices has grown exponentially. Such technology has the potential to solve many sociotechnical problems, by allowing data collection and communications to exist in the background of our daily lives as well as reach the most remote locations. As concerns over climate change and global warming continue to escalate, it is important to analyze the environmental impact of the exponential rise of the IoT. While the negative effects of the IoT to this point have been significant, including dangerous electronic waste and increases in energy usage, the current trend of IoT technology shows its potential to increase the efficiency of many destructive human processes, including manufacturing and building energy usage. This paradigm shift of society's primary technology domain—from personal electronics to autonomous cyber-physical systems—brings centralized intelligence and control to large-scale systems, allowing energy savings and waste reduction to occur on the same large scale.

Research Question and Methods

The motivating research question is: what are the environmental implications of the rise of the IoT and how can individuals and society as a whole use the IoT to help the environment? The research is a combination of discourse and network analysis, examining previous studies about electronic waste and its impacts on the environment and assessing current IoT technology to compile all positive and negative environmental effects of the IoT. Previous literature is crucial to determine pre-existing IoT technology that reduces energy consumption. For example, Shrouf et al. gave an overview of current IoT-based systems used in factories for energy management (Shrouf et al., 2014). Scientific studies about electronic waste and its impacts on the environment are investigated as well. One study looked at many common toxic materials in electronic waste, and used India as a case study to analyze the effects of these toxic materials on its inhabitants (Garlapati, 2016). Finally, the interactions among all the actors in the IoT social system are examined to understand where the effects on the environment originated from.

Background

The world is on the brink of a new technological revolution, one that will transform a society dominated by human-controlled electronic devices to one centered on computer-controlled systems continually collecting data and controlling the environment around them. This movement has been dubbed the ‘Fourth Industrial Revolution,’ dominated by the rise of the Internet of Things (Schwab, 2017). While previous Industrial Revolutions were driven by mechanical or electronic inventions, the Fourth Revolution is predicted to arise from a combination of the two: a new era of technology where computer systems are empowered to control data-gathering and physical tasks without human input (Figure 1).

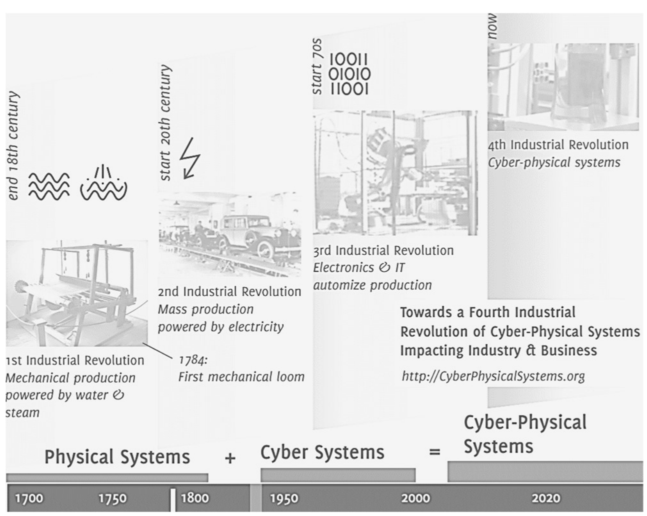

Figure 1. The first three Industrial Revolutions and predicted Fourth Industrial Revolution (Bloem, 2014).

The technology behind this revolution is the IoT, which consists of all network-connected objects (Xia et al., 2012). Some predictions ten years ago stated the IoT would reach 1 trillion nodes by 2020 (Evans, 2011), while data from 2019 showed this figure actually reached 26.7 billion (Maayan, 2020). It is imperative to carefully study, predict, and mitigate the negative side effects of the IoT, as these could quickly compound into significant issues due to the sheer scale of the IoT.

Each Industrial Revolution has led to increased CO_2 emissions, which in turn have been linked to global warming and climate change. **Error! Reference source not found.** shows the exponential increases in CO_2 emissions around the time the first Industrial Revolution began. With the potential of a new Fourth Industrial Revolution, it is important to quantify the IoT's predicted environmental impacts to best inform the development of IoT technologies.

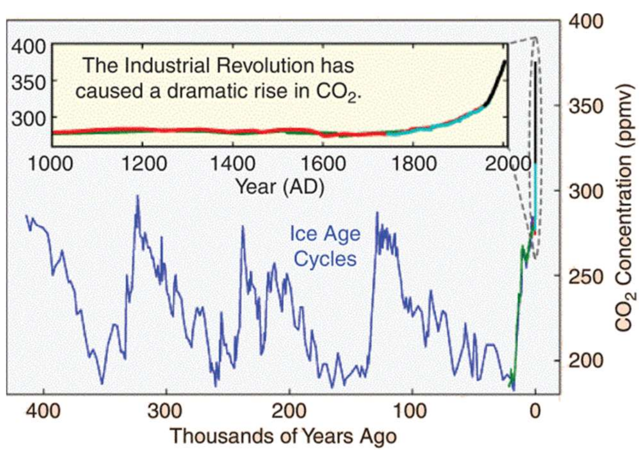

Figure 2. CO_2 concentration in atmosphere, showing significant increases since the late 1700s (Bose, 2010).

With regards to environmental impact, IoT devices are marketed as being sustainable because of their low power consumption and ability to decrease energy usage in various applications, such as in buildings or manufacturing. Most Science, Technology and Society (STS) research regarding the IoT has been about the social impacts of people being surrounded by always-on, always-listening electronic devices (Choi, 2014). The only environmental research has been to claim that the IoT can be used to benefit the environment, such as reducing electrical waste in companies (Gu, 2017). However, there has been little research done about the detrimental effects of the IoT on the environment. These effects are potentially more substantial given this planet's current trend towards global warming. This paper outlines the effects of the IoT on the environment by weighing the manufacturing and electronic waste costs of the IoT versus the environmental benefits of reducing human energy consumption using sensor networks.

Paradigm Shift and Actor Network Theory in the IoT

By analyzing the rise and proliferation of the IoT as a paradigm shift in society, the current and future effects of the IoT on the environment can be seen as the negative effects of technology on the environment (through waste and pollution) increasingly being counterbalanced by solutions humans are implementing *using* IoT technology to reverse these damaging environmental effects. The analysis in this paper determines whether the energy reduction from smart energy systems overcomes the production and energy costs of manufacturing, installing, maintaining, and disposing of IoT devices.

The IoT is a complex system involving many entities, comprising of:

1) Technology companies developing IoT devices and systems, who wish to push their products on consumers to make money.
2) Users, including everyone who is voluntarily or involuntarily affected by IoT systems
    a) Individual consumers, who purchase and install IoT devices to use in their lives.
    b) Business consumers, comprising of large companies who purchase and install large-scale IoT systems to assist their business and manufacturing.

c) Passive users, who are not consumers of IoT systems but are nevertheless affected by the IoT's widespread social and environmental impacts.

3) IoT devices, created by technology companies and marketed to individuals and businesses to be sold and installed; once installed, they collect data and perform the tasks for which they were designed.

4) Network connections, such as the Internet, whose data rates and distance ranges define how the technology companies design and market the IoT devices.

5) The environment, a passive actor affected by the choices the aforementioned entities make.

The interactions between these entities, with a focus on the effects of the interactions on the environment, are summarized in Figure 3*Figure 2*.

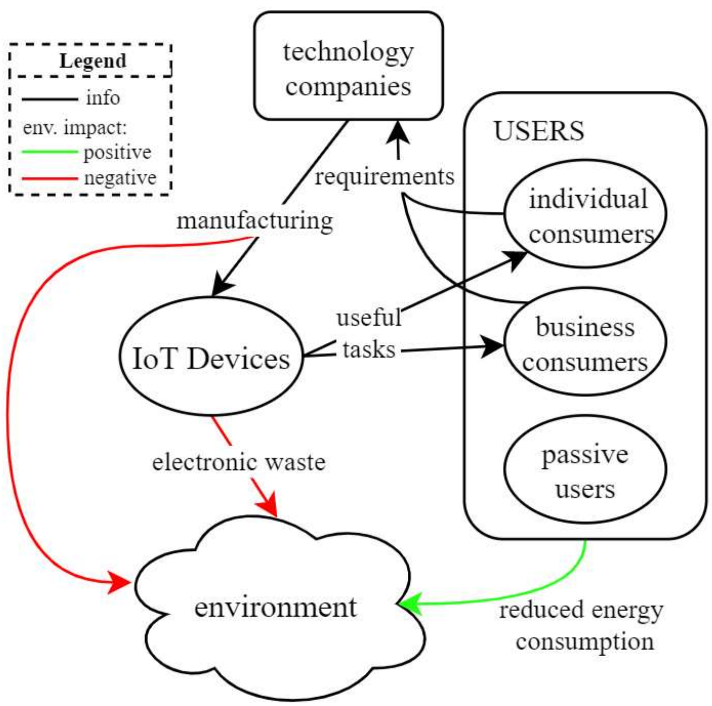

Figure 3. Interactions among entities involved in IoT system.

The effects of the IoT on the environment are characterized using actor-network theory (ANT). At the heart of determining the impact of the IoT on the environment are the interactions between the environment and IoT devices, the network, consumers, and technology companies, modeled using ANT (Cressman, 2009). While critics of ANT claim it is too broad in scope, this broadness allows the use of ANT as a framework, rather than a theory for the analysis of the proposed topic by analyzing the relationships between the entities listed above, in particular the impacts of these relationships on the environment.

The overall impact of the IoT on the remaining entities of this system is studied through the paradigm shift lens. Proposed by Thomas Kuhn, this theory states that throughout the history of science, there have been distinct shifts in its foundational concepts and experimental practices (Kuhn, 1964). As today's society transitions into its "Fourth Industrial Revolution," autonomous electronic systems and data-driven approaches are becoming dominant in the science and technology space. Such a shift is seen today in research in autonomous vehicles and artificial intelligence (AI), where humans are gradually being removed from the control loop of engineering systems, allowing the systems to be self-reliant and fully-autonomous. Thus the responsibility of studying and mitigating climate change will also gradually fall on data-driven approaches and self-powered, self-adjusting sensor systems.

Understanding the effects of the IoT on the environment is important because these effects will grow at the same rate as the number of IoT devices: exponentially. Unlike most sustainability efforts, the IoT is not something individuals can choose to "opt-out" of; IoT sensing systems will be in the background recording data, so before their proliferation it is important to gauge how these systems should be regulated.

Results and Discussion

The Internet of Things (IoT) is revolutionizing the interactions between humans and the environment; by establishing a network infrastructure of passive sensing and actuating devices, humans are able to better read and control their environment. While current applications of the

IoT have been human-centered, a growing field of research suggests the IoT can potentially revolutionize sustainability efforts to reduce climate change. This new technology field is known as the Green IoT. Spanning virtually all domains of technology, the Green IoT empowers society and individuals to better control their environment and actions, thus giving them the ability to lead "smarter" lives by reducing their environmental impact on the planet. Figure 4 outlines the domains and categories within the Green IoT.

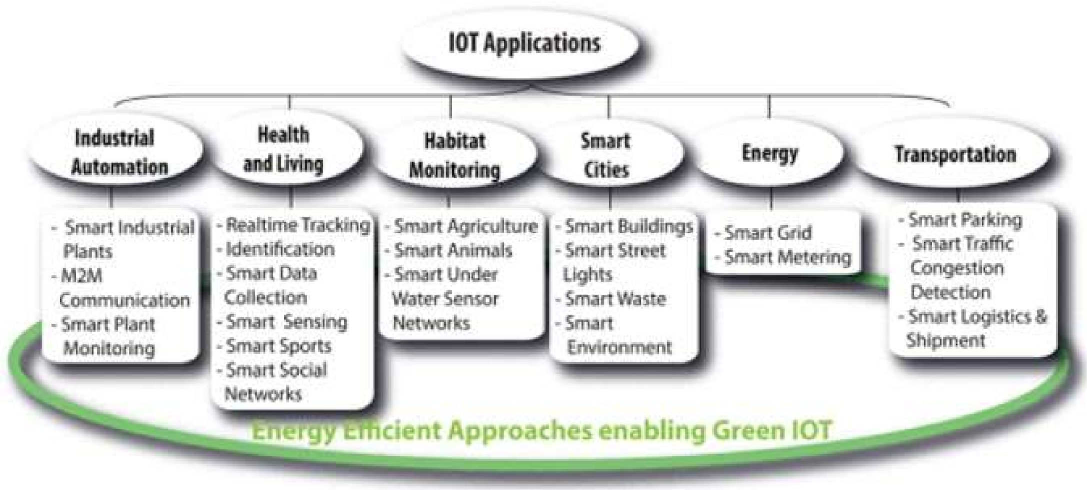

Figure 4. Domains within the Green IoT (Shaikh et al., 2017).

However, the rise of the IoT and the technology era of the last twenty years has inflicted negative effects on the environment as well. The number of personal electronic devices has continued to grow exponentially, subsequently resulting in an exponential increase in Waste from Electrical and Electronic Equipment (WEEE), also known as E-Waste. Materials used in electronic device production are often toxic and harmful to the environment, making them extremely difficult to dispose of. A typical E-Waste site in Taizhou, China is seen in Figure 5. With the third and fourth industrial revolutions in Figure 1 focusing on electronic devices and large-scale sensing systems, society has shifted to rely heavily on this technology, which in turn has significantly impacted the environment.

Figure 5. A typical E-Waste site in Taizhou, China, taken in 2013 (Gu et al., 2017).

Waste from Electrical and Electronic Equipment (WEEE)

A large concern of environmentalists is the growing problem of WEEE. The complexity and small scale of modern electrical and electronic equipment makes it extremely difficult to dispose or recycle. Both the vast quantity of WEEE and its toxicity in landfills has caused many countries to try recovering some of the raw materials from the waste, although wealthier countries often export this waste to developing countries, as seen in Table 1. Interestingly, the IoT both contributes to the rise of WEEE as well as alleviates some of its effects.

Country/ Region	From households (Mton)	To landfills, incinerators, storage (Mton)	Recovered domestically (Mton)	Exported/ imported (Mton)
USA	8.4	5.7	0.42	2.3/–
EU 25	8.9	1.4	5.9	1.6/–
Japan	4.0	0.6	2.8	0.59/–
China	5.7	4.1	4.2	–/2.6
India	0.66	0.95	0.68	–/0.97
West Africa	0.07	0.47	0.21	–/0.61

Table 1. E-waste numbers for several countries (Garlapati, 2016).

Electronics are often composed of many precious materials integrated onto one chip or device using complex laboratory procedures, making the materials virtually impossible to separate. Such chips, known as integrated circuits, are often in the form of microprocessors or other embedded devices. As of 2007, more than 98% of microprocessors or other similar electronics were embedded in products other than personal computers (Babu et al., 2007). Parallel to the rise of chips in many consumer products has been the decline in product lifetime; the lifetime of central processing units (CPUs), a component found in every computer, decreased from 4-6 years in 1997 to 2 years in 2005 (Babu et al., 2007). The growing consumer demand for electronics and the decreasing product lifetime, largely a result of the IoT, is causing a large rise in WEEE.

Many electrical parts, such as LCD screens and cathode tubes, contain chemicals that are toxic to humans and the environment, meaning they cannot be simply thrown in landfills. Meanwhile, the growing demand for the raw materials required in electronics has severely depleted their supply in nature, especially for precious and rare metals (J. Li et al., 2015): this incentivizes to poor individuals in developing countries to extract these metals from E-Waste and sell them for money. Thus, even after disposal, the electronics continue to harm the environment as mining of the precious metals from discarded electronics in developing countries causes hazardous electronic waste to be traded (J. Li et al., 2015). A 2015 study in China revealed that several heavy metals from WEEE had entered Chinese residents' bodies through the environment and their diet, with infants and children most affected by these toxins (Song & Li, 2015). Again, the exponential rise of electronics in this technology age has caused dangerous repercussions from their resulting disposal.

Electricity Usage

The technological boom of the 21st century has drastically increased electricity consumption in the world. While most consumer electronics are extremely low-power when compared with other human activities like manufacturing and transportation, the scale that these electronics are used at makes their power consumption not insignificant. In 2010 it was estimated that the information and communication technology industry produced around 2% of the global carbon footprint. However, it was estimated that by 2020 this contribution would rise to 6-8% (Dunn, 2010). Also, while these individual personal devices consume small amounts of energy, data centers that run many cloud applications consume large quantities of energy (Shaikh et al., 2017).

Nevertheless, current trends in electronic devices and electrical systems indicate that their environmental impact is falling. Innovations in circuit techniques and energy storage materials have driven down the power consumption of these devices. Figure 6 shows this progress and demonstrates that for low power budgets, a system lifetime of a decade may be attained (Blaauw et al., 2014). Furthermore, smart grid metering is another approach to reduce energy consumption at a large scale. The field of power electronics has allowed a large increase in efficiency of electrical equipment. For example, a load-proportional speed control for an air conditioner/heat pump unit can save up to 20% of energy consumed (Bose, 2010). While the development and resources required for such technologies are environmentally costly, their widespread effects allow the IoT to reduce human energy consumption.

Smart Manufacturing

Smart manufacturing is the process of using simple computing units and sensors to control manufacturing and improve energy and material efficiency in factories. IoT technology can collect and transmit real-time energy-consumption data, allowing analysis that informs system-level factory decisions (Y. Li et al., 2017). IoT sensor systems have been demonstrated to predict machine failure and initiate maintenance autonomously (Kai et al., 2017). Such predictive measures at the manufacturing-scale decreases equipment failure and extends the equipment lifetime by triggering maintenance proactively rather than retroactively.

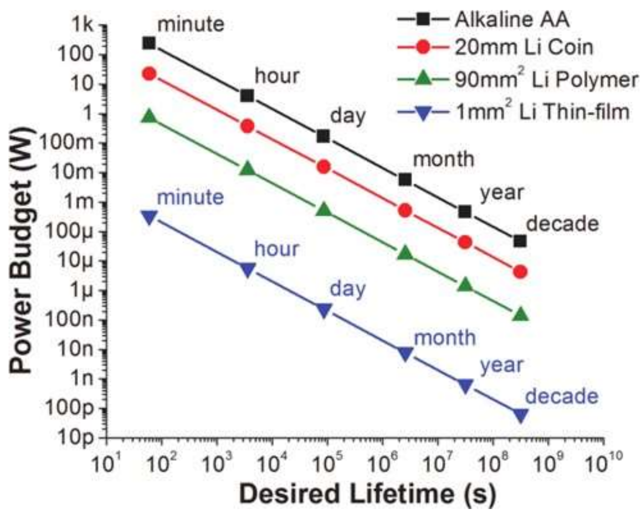

Figure 6. Battery capacity (Blaauw et al., 2014)

Finally, the data transmission capabilities of IoT technology allows the status of all stages of the manufacturing process to be transparent to all other stages, allowing for better predictions and optimizations to be made (Y. Li et al., 2017). Smart metering can be applied to manufacturing, employing production-level techniques such as minimizing energy usage when overall factory power consumption is high, and integrating energy data into the production (Lehner et al., 2015). Due to the sheer size and scale of manufacturing in today's industrialized society, data gathered can influence small production changes that lead to large effects on energy utilization.

Climate Monitoring

In the past decade, large companies and organizations have deployed IoT systems to monitor vital details about the Earth to better understand climate change. These IoT devices are able to gather data continuously, allowing more information about the environment to be available to individuals, policy-makers, and society as a whole. Microsoft's Eye on Earth promotes large-scale data gathering and open-source sharing to better inform people about the Earth ('Eye on Earth', 2017). IBM's IoT initiative, Smarter Planet, aims to add "smart" capabilities to power grids, food and water systems, healthcare, cities, and traffic systems in an effort to improve their efficiency ('Smarter Planet', 2012). These data-driven approaches to improving the world have the potential to give humans a much better understanding of their environment and available resources, and make better-informed decisions based on this data.

Individual Empowerment

Perhaps the most significant contribution of the IoT is to equip individuals with knowledge about their environment. The IoT informs individuals about the current state of the planet and their own power to positively affect the earth through conscious life choices. The shift in society is from a people-centric perspective to an information-centric perspective, where most decision-making is motivated by large amounts of data (Ray, 2016). Other research focusing on the paradigm shift from the IoT argue that the IoT allows decentralized influence of people on devices, and devices on their environments. At the local level, society can create technology platforms to solve the problems in their daily life as well as influence the political and social climate around them (Yury & Samoylova, 2017). For environmental advocates, this means any supporter may enact positive changes to reduce pollution and climate change. Empowering people brings the influence of the IoT to the individual, where small changes made by each person can have large effects on the planet.

Project Limitations

The research for this paper was limited by several factors. For one, the negative environmental effects of the IoT have not been studied extensively, as system-level modeling and research about the IoT is usually conducted or at least funded by parties motivated to spur interest for the IoT rather than approach the field objectively. Both Microsoft and IBM's IoT platforms for environmental research are marketed as being "sustainable" and against climate change, while their websites mention nothing about the adverse effects of electrical and electronic waste resulting from deploying thousands of sensor nodes. Instead, experts in the field should perform analyses of the projected amount of resources and energy required for future IoT endeavors and weigh these projections with the estimated energy savings from deploying such systems.

Conclusion

While current research, development, and production of electronic devices for the Internet of Things has negatively impacted the environment, as this technology is becoming more robust and low-power it has the potential to reverse these negative effects and reduce the human environmental footprint. The new era of Cyber-Physical Systems and the Internet of Things has caused an exponential increase in electronic waste and electricity usage. Meanwhile, progress in developing robust low-power systems and improving their manufacturing and recycling process is reducing energy and resource consumption in other fields such as factories and the electric grid. By installing the infrastructure for widespread sensing and communication, the amount of data and information about human and environmental activity may be gathered and processed centrally to better inform policy makers and individuals about how best to mitigate climate change. Such decentralized intelligence allows humans to remotely control virtually any domain regardless of its scale; in areas such as manufacturing, agriculture, or transportation, this control results in large increases in resource efficiency. Thus, the paradigm shift of technology from human-centered to data-centered allows sustainability efforts to have widespread effects.

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