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NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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NIST Advanced Manufacturing Series
NIST AMS 100-48

Cost-Effective Environmental Sustainability

A Focus on the Circular Economy

Douglas S. Thomas

This publication is available free of charge from:
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A Focus on a Circular Economy

Douglas Thomas
Engineering Laboratory
Applied Economics Office

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Abstract

Currently, global economies are using and contaminating resources faster than they can be regenerated. This resource depletion strains the economy and society today and into the future and is largely due to a series of misaligned incentives. Solving this problem begins by identifying these misalignments, identifying feasible solutions that realign incentives or addresses the results of the misalignment. This report examines the economics of a circular economy, focusing more on issues related to standards and technologies which might facilitate increased environmental sustainability.

Key words

recycling; circular economy; sustainability; economics; environment

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Executive Summary

This report focuses on understanding the processes, forces, and decision making that result in an unsustainable economy. It further seeks to identify cost effective solutions to alter these decisions. The unsustainable economy (i.e., an economy that expends limited effort to preserve resources) is, typically, a result of decisions made by individuals and firms from their stakeholder perspective. It develops primarily as a result of a misalignment of incentives where those that bear the costs of increased sustainability do not receive commensurate benefits. Successful solutions to this problem will tend to alter the economy so that the logical and rational outcome for the individual or business matches that of society. Alternatively, successful solutions might mitigate negative outcomes. This report focuses on standards and technologies as a solution to facilitating a more sustainable economy. Four means of achieving sustainability are identified: increasing product longevity, reusing/repairing products, reducing material and energy use, and recycling.

Product Life Expectancy and Repairability: Extending the useful life of products is an effective means for reducing environmental impact for durable goods (e.g., automobiles, machinery, computers, and appliances). Three means for extending the use of a product is to design the product to last longer, reusing a product, and repairing a product rather than discarding it. A 50 % increase in life expectancy of a product decreases the needed replacements by up to approximately 33 %, which can equate to a 33 % reduction in environmental impact to produce that type of good and a potential savings of up to $316.6 billion in U.S. consumer savings. A 100 % increase in life expectancy reduces needed replacements by up to 50 %, which can equate to up to a 50 % reduction in environmental and up to $474.9 billion in savings. Note that these are upper bound estimates. Producers have limited means for signaling their product has a longer life expectancy, likely resulting in decreased sales of long-life expectancy products. The following needs were identified:

- Ability to differentiate product brands and models by life-expectancy
- Ability to differentiate product brands and models by repairability

The ability to differentiate quality products can increase the longevity of products, thereby reducing environmental impact, benefit consumers by not having to replace products as frequently, and disproportionally benefit U.S. manufacturers, as they likely have a tendency to use differentiation as a competitive strategy. Energy Star is an example of successfully differentiating products. In the case of Energy Star, it is by the amount of energy the product consumes. It is estimated that for every dollar invested into Energy Star, there are $350 in energy savings (U.S. Environmental Protection Agency and U.S. Department of Energy 2022). In 2020 alone, Energy Star helped save $42 billion in energy costs (U.S. Environmental Protection Agency and U.S. Department of Energy 2022). This program addresses a problem that is similar to differentiating by life-expectancy in that both can harness the savings that consumers experience in order to reduce environmental impact.

The type of differentiation that Energy Star facilitates can also be used to extend the useful life of products. The ability to differentiate by life-expectancy is similar to the potential NIST action item in NIST Special Publication 1500-204 regarding expected lifetime certification. There are many needs for extending product longevity; however, differentiating products by life-expectancy and repairability stands out as it can motivate manufacturers and consumers to work toward solving the other challenges. That is, it can have a chain reaction. Additionally, other efforts to increase life-expectancy and repairability may have limited impact if manufacturers have little or no incentive to lengthen the useful life of a product and consumers have no ability to select the longer lasting products.

Recycling: Recycling is an additional avenue for decreasing environmental impact. Two key topics are plastics and metals which are a limited resource that often contaminate the environment when discarded; constitute a significant amount of the material in technology products, including electronics, automobiles, and appliances; and they are often recycled at a low rate.

Plastics Recycling: Currently, a mere 8.7 % of plastics are recycled (U.S. Environmental Protection Agency 2021). It is estimated that if we recycled all plastics it would result in a 25 % decrease in carbon equivalent emissions (Zheng and Suh 2019). However, the cost of using recycled plastic material can be as much as twice as high as virgin material for some applications. Virgin plastic is sourced from raw materials that are concentrated at relatively few locations while recycled material is widely dispersed, combined with other materials, and often contaminated. An analysis revealed that 20 % of plastic collection efforts had a 15 % return on investment or higher for recycling, 50 % had positive returns but were less than the selected 15 % threshold for investment, and 30 % had negative returns (Gao 2020). There are many challenges to recycling plastic: the material typically degrades after being mechanically recycled, there are problems with contamination, there are many types of plastic that cannot be recycled together limiting economies of scale, plastics are often integrated into a product with other material types (e.g., metal), and there are many variations in additives that need to be addressed. Additionally, there is not always a customer for recycled material. The following needs were identified in plastics recycling:

- Aggregate streams to increase volume and economies of scale, which could include:
    - Understanding the economics of individual plastic streams, including which ones, if any, could be substitutes for one another
    - Reducing the number of plastic types used
    - Standardizing and/or tracking the additives in plastic
- Low cost means for
    - Separating post-consumer plastic types
    - Preventing and/or removing contaminants
- Ability to differentiate product brands and models by recyclability

Some of the potential NIST action items in NIST Special Publication 1500-204 relate to the needs above, including the action items on research on purity tolerances for post-consumer feedstocks; rapid material composition fingerprinting; publicity of product materials/composition; and AI and robotics to identify, assess, and/or disassemble products. It is important to note that the last need listed above is unique in that the ability to differentiate products by recyclability can motivate manufacturers and consumers to work toward solving sustainability challenges, resulting in a chain reaction.

Metal Recycling: Despite scrap metal having a high value, 29 % of discarded nonferrous metal and 54 % of ferrous metal ends up in a landfill. Out of 60 metal types, 34 are recycled at a rate of less than 1 % (Reck and Graedel 2012). The difficulty in separating alloys emphasizes the need to consider the end of life when designing a product. For most unrecycled metals, it is estimated that a price increase of one or two orders of magnitude might be needed to make them essentially economical. Research suggests that factors such as the concentration of metal in a product has more impact on the recycling rate than the value of metals, which emphasizes the need to consider product design regarding increased recycling. The following needs were identified:

- Ability to differentiate product brands and models by recyclability
- A low cost means for identifying and separating materials
- A low cost means for reprocessing materials, which might include
    - Reducing the material variation within a product
    - New technologies and innovations in reprocessing

The NIST action items in NIST Special Publication 1500-204 regarding materials/composition; material science for the reduction/replacement of rare materials; and AI and robotics to identify, assess, and/or disassemble products relate to the needs listed above. Again, it is important to note that differentiation by recyclability stands out as it can have a domino effect where producers and consumers might be motivated to solve sustainability challenges.

Common Barriers to Sustainability: There are some common barriers that inhibit solutions to creating a sustainable economy. Research in manufacturing and many other fields tends *not* to be selected/guided using measures of return such as return-on-investment or benefit-cost ratio to identify those that will have the largest impact per dollar of investment. There is also a mismatch of incentives for researchers, as they are rewarded for increasingly complex and innovative discoveries or findings published in journal articles. If superior solutions are simple or involve reiterating previous findings, the reward to the researcher is often significantly diminished. Another barrier is that there are frequently misunderstandings among the general public. People and organizations often sensationalize information, selecting statistics, data, and/or language that is often more appealing to their audience but does not necessarily represent an accurate depiction of events or reality. This can result in popularizing sustainability solutions that are suboptimal. A final barrier is that there is a tendency to value the 'me and now' – that is, the tendency to value short-term individualized rewards. Frequently, sustainability involves sacrificing resources for benefits to society that occur in the future, often making it difficult to gain broad support.

1. Introduction

1.1. Background

This publication focuses on sustainability (i.e., preserving resources for long-term prosperity), including concepts of a circular economy (i.e., reusing resources). Currently, global economies are using resources and contaminating resources faster than they can be regenerated. This resource depletion strains the economy and society today and into the future and is largely due to a series of misaligned incentives. Solving this problem begins by identifying misalignments and feasible solutions that realign incentives to improve outcomes. Sustainability or sustainable development is often the term used to discuss solutions to the depletion of resources, including decreasing pollution and threats to human health. A commonly cited definition of sustainable development states that it is, "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations 1987).

1.2. Purpose

The purpose of this report is to discuss the economics of facilitating a sustainable economy. This includes identifying reasons why unsustainable practices occur and identifying cost effective solutions. To do so requires understanding under what circumstances one solution is more cost effective than another or when they can or should be used together.

1.3. Scope and Approach

Since this report focuses on the economics of sustainability, there is only limited discussion on the technological details of sustainability. To efficiently and effectively develop a sustainable economy, it is necessary to understand the processes, forces, and decision making that result in an unsustainable economy. Thus, the focus of this report is on decisions and reasons why producers and consumers choose unsustainable practices and products. Further, it seeks to identify cost effective solutions that alter these decisions or diminish their negative impacts. This report tends to discuss issues related to standards and technologies for facilitating a sustainable economy as opposed to, for instance, regulations, taxes, or reducing consumer consumption.

2. Causes and Potential Solutions to an Unsustainable Economy

The causes and potential solutions to an unsustainable economy are complex. This section discusses the general forces that result in unsustainable activities and the categories of solutions that might bring about sustainability.

2.1. Incentives and Market Forces

The free market frequently works well for determining how resources should be allocated. However, there are barriers that prevent the free market from reaching an optimal solution in all situations. When this happens, it is typically called a market failure. Multiple market failures serve as a barrier to the adoption of a sustainable economy. Many of these, amount to mismatches in incentives. Figure 2.1 maps the life cycle of a product and its materials and identifies some challenges to adopting a sustainable economy. One challenge is a mismatch in incentives between the producer and consumer. Producers have a limited ability to signal to consumers that their product performs better or lasts longer than their competitors' product (see #3 in Figure 2.1). Producers can offer warranties, guarantees, or build a brand reputation; however, warranties and guarantees can be misleading measures of quality. The difference between

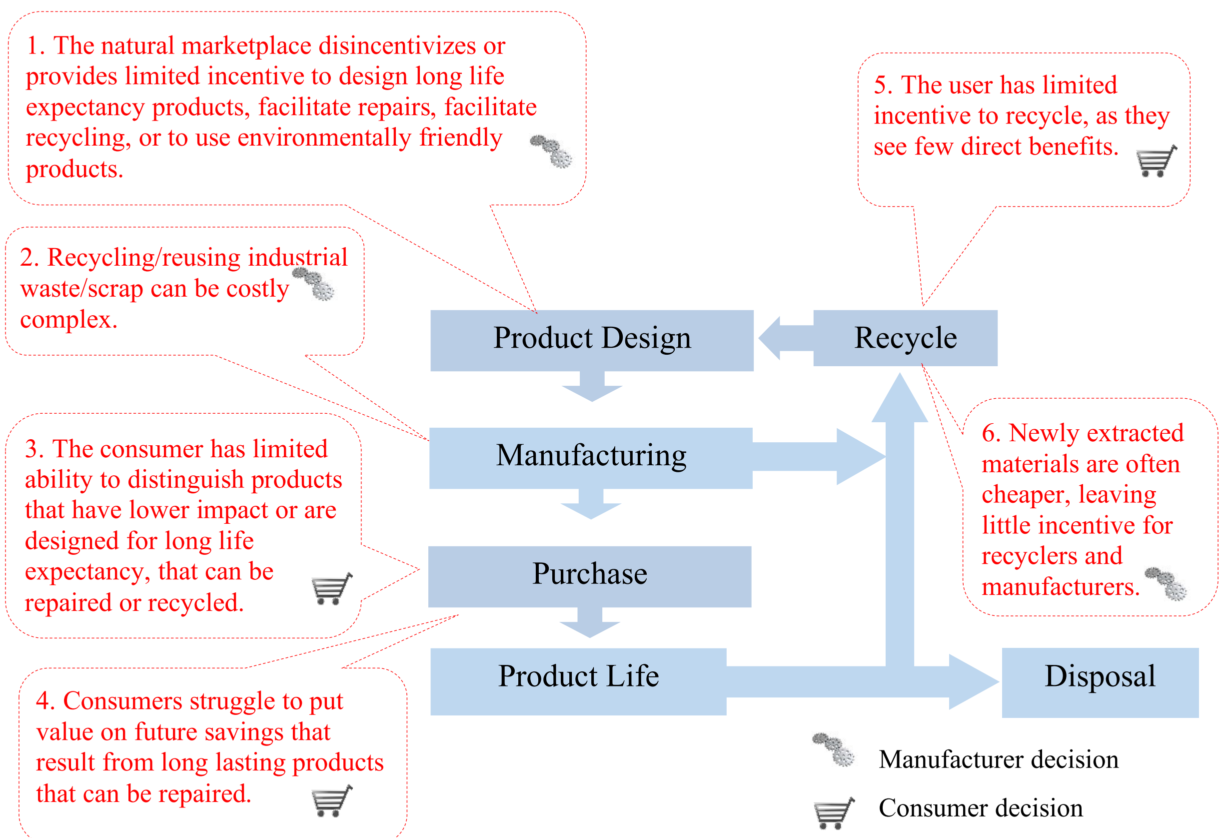


Figure 2.1: Economic Challenges to the Adoption of a Sustainable Economy that occur in a Free Market

low life-expectancy and high life-expectancy products can be obscured with advertising, having a brand with a mix of low and high performing products, offering warranties with deductibles and prorated replacement offset by simply increasing the price of the product to cover the replacement of products that prematurely fail. Even when producers can differentiate their products, consumers often under value future savings (see #4 in Figure 2.1). This leaves little incentive for producers to design long lasting products that can be repaired and/or reused (see #1 in Figure 2.1).

Another challenge is a mismatch in incentives due to externalities where the manufacturer and the consumer do not bear the full cost of producing and using a product, as the environmental impacts of a purchased product are experienced by people other than just the producer/consumer. This results in a lower than optimal incentive in designing products and processes to reduce environmental impact (see #1 in Figure 2.1). It also diminishes the incentive for consumers to recycle (see #5 in Figure 2.1) and for producers to purchase recycled material (see #2 and #6 in Figure 2.1), as they do not bear the full cost of newly extracted materials.

The challenges can be grouped into three primary incentive misalignments:

- **Design for longevity/reuse/repair/recycle and using materials/energy with a smaller footprint**: costs of design and production are borne by the manufacturer while benefits are experienced by society (i.e., reduced environmental impact).
    - **Complicating factor**: consumers struggle to distinguish products designed for longevity/reuse/repair or ones that use environmentally friendly materials/energy
    - **Complicating factor**: consumers struggle to value future savings/benefits
    - **Complicating factor**: in addition to the costs of design, manufacturers can experience diminished sales when products last longer
    - **Complicating factor**: in addition to the costs of design, reusing materials can be complex with many challenges
    - **Complicating factor**: Longer lasting products may not be used to their full capacity
- **Recycling**: The user and manufacturer bear some costs of recycling (e.g., separating, transporting, and fees) while the benefits are experienced by society as a whole
    - **Complicating factor**: societal benefits are not always obvious to society
    - **Complicating factor:** domestic and international taxes, Subsidies, and regulations related to fossil fuels or recycling can affect the economics of recycling
- **Decreasing waste, energy use, and material use**: Producers and consumers bear the cost of purchasing or using methods/items that decrease waste, energy, and material use while society experiences the benefits
    - **Complicating factor**: It isn't always clear what method or product results in decreasing waste, energy use, and/or material use

These misalignments mean that there is a system failure. That is, the current system of exchange does not address these problems. Even if a manufacturer wants to participate in sustainable development, market pressure can significantly diminish their ability to do so. This pressure could even drive businesses that engage in sustainable practices out of business, leaving only those firms that do not invest in sustainability, as they do not have to bear the extra cost. Consumer preferences can pressure firms to increase sustainability; however, without any reliable means for discerning sustainable performance, it may only result in the appearance of sustainability. Moreover, the unsustainable economy is, typically, a result of logical and rational decisions made by individuals and firms from their stakeholder perspective.

2.2. Potential Solutions to Create a Sustainable Economy

There are several potential solutions to mitigate the challenges to a sustainable economy. Kirchherr et al. (2017) presents a summary of solutions; however, they present them as barriers to a circular economy (i.e., lack of solutions). The four categories of solutions include the following: Cultural, Technological, Market, and Regulatory. For this report, we will use an altered version of this list for categorizing solution types that create a sustainable economy:

- **Cultural solutions**: putting ethical or moral pressure on companies and/or individuals to adopt practices related to a sustainable economy
- **Information dissemination**: educating companies and/or individuals on issues related to a sustainable economy
- **Technological solutions**: developing new technologies or adopting existing technologies that facilitate a sustainable economy
- **Standards**: developing standards that facilitate the adoption of practices related to a sustainable economy
- **Legislation**: Mandating practices related to a sustainable economy and/or implementing taxes, providing subsidies, or providing other policy-based incentives for adoption of such practices

The solutions either aim to reduce the effect of the misalignment (e.g., reduce costs, increase incentives, or reduce the negative outcomes directly) or realign the incentives for a sustainable economy so that the logical and rational outcome for the individual or company matches that of society. Cultural solutions, for instance, could create an additional cost in the form of guilt if one does not participate in a practice related to the sustainable economy. Other examples can be found in product boycotts or in developing new technologies that can reduce the cost for manufacturers to use recycled materials. Note that this report focuses on technological solutions and standards.

The list above differs from Kirchherr et al. (2017) in that it does not have a “Market” category. This was removed as all these items affect the market, and our barrier list describes market conditions. The list above also includes two additional categories: “Information dissemination” and “Standards.” “Information dissemination” could be considered a component within other categories. It is broken out here as it is often overlooked. Misperceptions are common and can become significant barriers to progress in addressing societal issues. “Standards” could have been considered part of the “Technological Solutions;” however, it is not a perfect fit because it is focused on consistency instead of innovation of technologies. The list above also changes the “Regulations” category from Kirchherr et al. (2017) to “Legislation” to include taxes, purchasing and access requirements, and subsidies, as some might not see these as regulations.

The solutions listed above work through a number of means, including

- Increasing longevity of products
- Producing energy using environmentally friendly technology
- Recycling
- Reducing material and energy use
- Reusing/repairing products
- Using products/materials with a smaller impact

Individual solutions can be categorized by solution type, the means by which they achieve sustainability, and their primary effect on the misalignment of incentives (i.e., increase costs of unsustainable activities, decrease the cost of sustainable activities, realignment of incentives, or mitigate negative externalities), as illustrated in Table 2.1. For instance, consider a standard that develops a metric measuring the expected life of a product. This would allow consumers to reliably predict and compare product life-expectancies so that, if they want, they can choose longer lasting products. This would fall under the “Standards” row and “Increase Product Longevity” column. In terms of sustainability, this standard realigns incentives, which is represented with the symbol ʘ. Another example might be a material standard for plastics that standardizes plastic additives. This might increase the cost of producing some products; however, it would decrease the cost of recycling through economies of scale (i.e., decrease the cost of sustainable activities, which is represented with -$), as more plastics could be recycled together. That is, if a firm decides to increase their sustainability by using materials that can and will be recycled, the true cost of doing so is decreased as a result of the standard. Otherwise, the firm might, for instance, have to invest in developing recycling facilities specific to their material. This standard would fall under the “Recycle” column and “Standards” row, as it is a standard that facilitates recycling.

Table 2.1: Intended Primary Effect of Public/Industry Level Research Investments by Solution Type and Means for Achieving Sustainability

Solution Type	Means for Achieving Sustainability: Increase product longevity	Produce cleaner energy	Recycle	Reduce material and energy use	Reuse/repair products	Use low impact products/materials
Cultural solutions	$	$	$	$	$	$
Information dissemination	-$, Θ	-$	-$	-$	-$, Θ	-$
Technological solutions	-$	-$	-$	-$	-$	-$
Standards	-$, Θ	-$	-$	-$	-$, Θ	-$
Regulations, taxes, and subsidies	-$, $, Θ, ֍	-$, $, Θ, ֍	-$, $, Θ, ֍	-$, $, Θ, ֍	-$, $, Θ, ֍	-$, $, Θ, ֍

Primary Effect on the Misalignment of Incentives

$ Increase the costs of unsustainable activities

-$ Decrease the cost of sustainable activities

Θ Realignment of incentives

֍ Mitigate negative externalities

2.3. The Circular Economy, Bioeconomy, and Green Economy

Three terms are popularly discussed regarding sustainability: circular economy, bioeconomy, and green economy. Each has a slightly different focus but often overlap one another. The circular economy emphasizes regenerative production-consumption systems (Amato and Korhenen 2021) and includes recycling, reuse, remanufacturing, repair, and product longevity among other things (Ekins 2019). Descriptions of a circular flow of materials appears as early as the mid-1970's (Ekins 2019). The bioeconomy tends to focus on utilizing biological resources for developing and producing goods and services while green economy tends to focus on renewable energy, although it also includes elements of reducing material and energy inputs, recycling, and reuse (Amato and Korhenen 2021). There are numerous publications that discuss and define circular economy, bioeconomy, and green economy that will not be reproduced here.

It is important to note that circular economy, bioeconomy, and green economy tend to refer to sets of solutions to the misalignment of incentives previously discussed. However, this is only partially true for bioeconomy, as it refers the characteristics of a manufacturing process; thus, alignment only applies regarding environmental or sustainability issues. Despite language around these terms, they are not end goals by themselves, but rather a means for achieving a sustainable economy. The language used in reference to the terms can, misleadingly, implicate them as being the end goal, overlooking the objective of sustainability. Having the term "economy" in each term also misleads to the idea of them being an overall end goal or solution.

Although the terms circular economy, bioeconomy, and green economy are useful and commonly used, their definitions can be vague with many seeking to refine them. For instance, there are research papers that aim to understand the terms by systematically examining their usage (e.g., Homrich et al. 2018). The terms also often overlap one another. For instance, bioplastics are considered both green and circular, though they may not necessarily be either. There can also be tradeoffs between one another, and they are not always compatible with each other (Amato and Korhenen 2021). Thus, one solution might need to be selected over another. These challenges can make the terms limited in researching, developing, and identifying solutions to develop a sustainable economy. Despite these challenges, the terms are rhetorically pleasing, making them useful for gaining support. Researchers and decision makers, however, need to exercise care in orienting research and decisions around these terms, as they have some challenges. To develop the most sustainable economy possible, research and decisions must be based on their return on investment in terms of sustainability.

3. Economic Evaluation of Industry/Societal Level Investments

Given that there are limited resources for investment, to produce the most sustainable economy possible it is necessary to identify those solutions that have the largest return on investment for sustainability. Thomas (2017) presents a guide for investment analysis, which discusses net present value, internal rate of return, and uncertainty analysis among other items. These methods, presented in Appendix A and Appendix B, can be used along with methods for examining environmental impact to identify solutions that have the highest return. For instance, some environmental impacts can be converted to carbon equivalents and then to dollar values using an estimate for the cost of carbon (EPA 2016). This report will utilize a slightly altered approach where the benefits remain in units of environmental impact with different impact types weighted using the Analytical Hierarchy Process (see Appendix C), as calculated in NIST's Manufacturing Cost Guide (Thomas 2020). These methods are not from the natural sciences, but drawn from the decision sciences.

A benefit-cost ratio is presented in graphical form like that from Thomas (2019), which presents a guide to evaluating potential research and development investments in the manufacturing industry. This will give a visual aid for identifying relative returns (see Figure 3.1). The projects in the figure are drawn as boxes to represent a range of costs and benefits. The benefit cost ratio for projects can be visually examined by drawing a

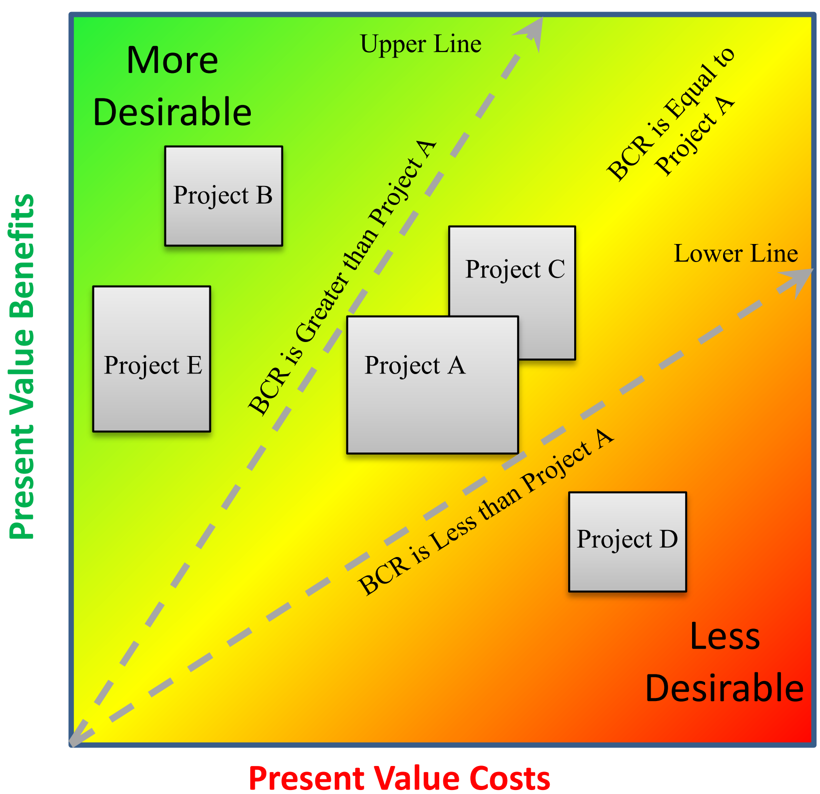


Figure 3.1: Graphing Costs and Benefits and the Benefit-Cost Ratio (BCR)

line from the origin through the top left corner of the projects graph and another through the bottom right corner, as illustrated for Project A in Figure 3.1. Because the slope of the line represents a constant benefit cost ratio at the intersecting point of the project, any projects, or portions thereof, that lie above and to the left of the upper line outranks the project (i.e., Project E and Project B outrank Project A). Any projects that lie below and to the right of the lower line are outranked (i.e., Project A outranks Project D). Projects that lie between the upper and lower lines have overlapping benefit cost ratios with Project A.

When estimating the return for an investment in sustainability, it is important to consider the probability of success. An investment analysis is a forecast or prediction of the results of one's decisions. Like any model, this forecast has assumptions and uncertainties. Investments in sustainability can have a significant amount of uncertainty. For instance, there is uncertainty for how society might respond to public service announcements or how manufacturers might respond to new regulations, costs, or standards. Moreover, it is important to incorporate these uncertainties when evaluating the return for an investment. Society level sustainability typically includes changing the behavior of multiple people; thus, two primary factors for success are the number of people that need to change their behavior and the magnitude of the behavior change. High numbers of people are more difficult to reach and as the number of people being asked to change increases, there is an increase in the number of people who might create barriers. Changing patterns of behavior can be difficult even if a person wants to change. The more change that is being asked of them, the more difficult it will be to implement. A third factor is how the change relates to incentives for the person/organization being asked to change. The more a change is inconsistent with individual incentives, the more difficult it will be to implement. Thus, the success of a sustainability solution increases as the number of people needed to change decreases, the magnitude of change decreases, and the incentives increase, as illustrated in Figure 3.2.

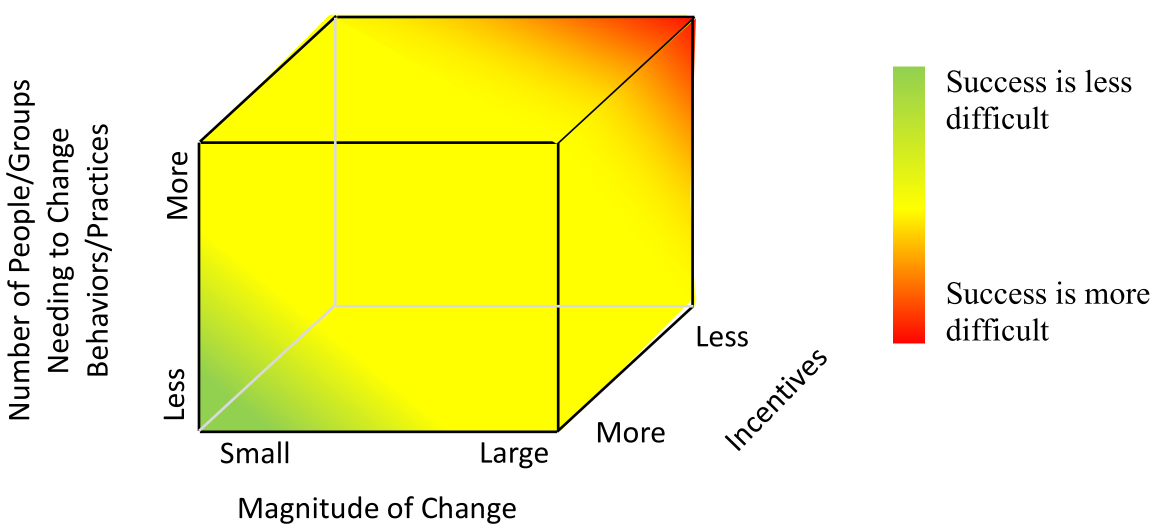


Figure 3.2: Additional Challenges, besides Cost, to Creating a Sustainable Economy

4. Reuse, Repair, and Product Longevity

An effective way to reduce the environmental impact of producing a product is to produce fewer of them. If a product lasts longer, consumers tend to replace them less frequently, thereby reducing the number of items manufactured. Extending the useful life of a product generally applies more to durable goods. As shown in Table 4.1, discrete tech products account for 6.9 % of the U.S. economy's environmental impact and discrete products account for 14.2 %. As shown in Figure 4.1, if a product's life expectancy increases by 50 %, it decreases the needed replacements and commensurate environmental impacts by approximately 33 %. A 100 % increase in life expectancy reduces needed replacements and commensurate environmental impacts by 50 %, if products are used to their end of life. In 2020, consumers spent approximately $949.8 billion on vehicles, appliances, tools/equipment, and other electronics. Using Figure 4.1, a 50 % increase in the life expectancy of these items (e.g., increasing the life expectancy of a washer from 12 years to 18 years) could translate to up to a $316.6 billion annual consumer savings (few purchases) or, on average $2588 per household. Appliances alone amount to $21.1 billion. However, this is likely an upper bound limit as it is important to note that some consumers replace these items for aesthetic reasons rather than out of necessity, which would reduce the estimated savings.

Table 4.1: Environmental Impact of Manufactured Goods by NAICS Code (Percent of U.S. Economy's Impact)

NAICS Code and Description	Contribution to U.S. Economy's Environmental Impact (%)
Food, Beverage, and Tabaco Products (NAICS 311-312)	29.4
Discrete Products (NAICS 313-323, 327-332, 337-339)	14.2
Discrete Tech Products (NAICS 333-336)	6.9
Process Products (NAICS 324-326)	35.6
Plastics (NAICS 326110-326190)	2.4
Plastic Bottles (NAICS 326160)	0.2
Plastic Packaging and unlaminated film/sheet (NAICS 326110)	0.6
Total (does not equal sum)*	76.6

* The total does not equal the sum, as there is overlap between categories. For instance, automobiles contain plastics, which are a separate category.

Source: Thomas, Douglas. (2020). "The Manufacturing Cost Guide" and "The Manufacturing Cost Guide: A Primer Version 1.0." NIST Advanced Manufacturing Series 200-9. https://doi.org/10.6028/NIST.AMS.200-9

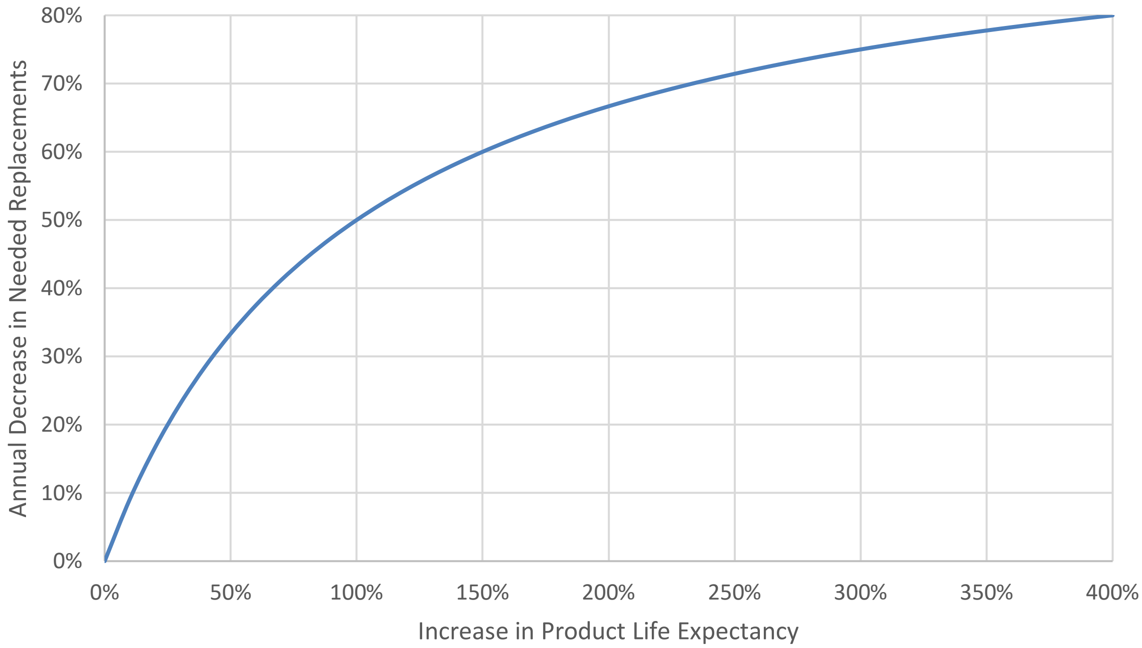


Figure 4.1: Calculated Decrease in Annual Replacements Needed by Increased Product Life Expectancy

Unfortunately, producing fewer products directly contradicts the business mantra of increasing sales. Thus, as stated previously, a 50 % increase in life-expectancy can reduce needed replacements by 33 %, but this also means that it can reduce the number of sales by 33 %. Planned obsolescence and deliberately shortening the life expectancy of a product has become commonplace (Cooper 2016). Additionally, manufacturers can struggle to charge higher prices for increased quality; thus, they have limited incentive to design for a long life-expectancy product. To profit from a higher quality product, a manufacturer must be able to differentiate their product from the short life-expectancy product. Otherwise, the average consumer is not willing to spend more for the higher quality. There are some signals that can be used; however, they are limited in their effect. Generally, consumers can only make an 'educated guess' as to the quality and life expectancy of a product (Cooper 2012). Standards to indicate life expectancy might increase the purchase of longer lasting products and various approaches are possible (Cooper 2012). Research has suggested that consumers are willing to pay more for quality (Bertini et al. 2011).

Because the U.S. expends significant resources on education and technology, and since the U.S. has high labor costs, it is likely to have more companies that use differentiation as a competitive strategy as opposed to a low-cost competitive strategy. That is, U.S. companies tend to compete using quality or brand reputation rather than price. This is evidenced in that U.S. as a brand is ranked 13th out of 75 countries (FutureBrand 2020). Thus, the ability to differentiate quality products is likely to disproportionally benefit U.S. manufacturers. Moreover, the ability to differentiate long lasting products not only benefits consumers and the environment, but also benefits U.S. manufacturers. Energy Star is an example of successfully differentiating products. Energy Star differentiates products by the amount of energy they consume. It is estimated that for every dollar invested into Energy Star, there are $350 in energy savings (U.S. Environmental Protection Agency and U.S. Department of Energy 2022). In 2020 alone, Energy Star helped save $42 billion in energy costs (U.S. Environmental Protection Agency and U.S. Department of Energy 2022). This program attempts to solve a problem that is similar to differentiating by life-expectancy in that both harness the savings that consumers experience in order to reduce environmental impact.

Three means for extending the use of a product is to (1) design the product to last longer, (2) reusing a product, and (3) repairing a product rather than discarding it. When asked how long individuals would like to use their digital devices, a survey of Europeans showed that 64 % wanted them to last at least 5 years, including 26 % that indicated at least 10 years assuming there is no significant drop in performance (European Commission 2020). Thus, many consumers do have a desire to utilize digital devices longer. As seen in Table 4.2, the most common reason for replacing a digital device was that it broke down, accounting for 38 % of replacements followed by a decline in performance (30 %) and software stopped working (18 %). For appliances, Statista estimates that 88% of home appliance replacements are due, in part, to broken devices (Kunst 2019). Moreover, consumers want their products to last but must replace them because they break or lose functionality.

Unfortunately, the expected lifespan of products is often unclear at the time of purchase. For instance, a report from the Lawrence Berkeley National Laboratory estimates the life expectancy of a freezer to be 21.21 years while Appliance Magazine estimates 11 years as does consumer reports (see Table 4.3). Other similarly large differences occur for other appliances as well. Cell phones are often cited as lasting anywhere from 2 years to

Table 4.2: Survey Responses Regarding Digital Device Replacement

Think about the last digital device (e.g., mobile phone, tablet, laptop, etc.) you replaced. What were the main reasons for purchasing a new device (choose up to 3 answers)?

Reason	Percent of Respondents
You broke your old device	38
The performance of your old device significantly deteriorated	30
Certain applications or software stopped working on your old device	18
You wanted a device with new features or services	14
You received a new device as part of a contract with your provider	12
You like to have the most up-to-date devices on the market	6
You no longer liked the look of your old device	5
Other (spontaneous)	3
You haven’t replaced a digital device (spontaneous)	7
You don’t own any digital devices (spontaneous)	5
Don’t know	1

Source: European Commission 2020

4 years. Statista, for instance, estimates the life span of smartphones to range from 2.58 years to 2.96 years between 2014 and 2019 (O'Dea 2022). Consumers' knowledge about the life span of a product is largely based on anecdotal evidence and other error prone evidence (Cooper 2016). The uncertainty in the lifespan of different products makes it unclear as to the extent that the lifespan can be extended. For a consumer to incorporate the product lifespan into a purchase, they would need to be able to discern the lifespan of different product brands and models. Given the variation and difficulty in estimating the lifespan of general product categories (e.g., refrigerators), consumers have little chance of accurately identifying the difference in life expectancy for their individual products. Moreover, consumers have little or no ability to discern the characteristics of one of the largest impacts on sustainability – the life expectancy of the product they are purchasing. This challenge is also identified in NIST Special Publication 1500-204 where "expected lifetime certification" is proposed as a NIST action item (Schumacher and Green 2021).

In addition to the difficulty in differentiating products, consumers struggle to value future savings that might occur from longer lasting products. Behavioral research in economics and psychology (e.g., Ikeda et al. 2010, Bickel et al. 1999, O'Donoghue and Rabin 2015)

Table 4.3: Appliance Life Expectancy, Years

	Appliance Magazine*	Mean from OSTI article*	Consumer Reports**
Freezer	11	21.21	11
Refrigerator	12	17.68	13
Water heater, electric	13	9.65	11
Water heater, gas	11	11.99	10
Room air conditioner	9	8.36	10
Central air conditioner	11	18.04	15
Boiler, gas	20	17.54	21
Furnace, gas	15	22.61	18
Heat pump	12	14.64	-

* Lutz 2011
** Consumer Reports 2019

have demonstrated that there is a tendency in human decision making to overvalue or give preference to immediate rewards over future rewards, which is often referred to as "present bias." This tendency means that consumers are likely to undervalue the savings that might result from purchasing products with a longer life expectancy. Moreover, there are incentives for both producers and consumers for producing and consuming short life-span products, resulting in less expensive replacements that tend to have low quality (Laitala 2021). An interesting solution to some of these challenges was implemented in Vienna, where they have subsidized repairs using a voucher system that provides up to 200 euros for consumer electronic repairs (Austrian Press 2022).

Consumers have also come to expect products to only last a short time. For instance, a survey of consumers revealed that a cell phone might be expected to last up to two years, a computer might last up to 4 years, and a washing-machine might last up to 6 years despite the technology available to make these items last significantly longer (Cox et al. 2013). Consumers sometimes discard functioning electronics to have the latest technology. An interesting solution that has been proposed is to produce electronics that are modular. For instance, Proske and Jaeger-Erben (2019) propose producing modular cell phones where different components can be upgraded.

As manufactured goods have become more complex, consumers understanding of these products have diminished and their ability to repair them has been hindered (Cooper 2012). Additionally, products can be designed to either hamper or facilitate repairs. For instance, a product may be difficult to open, have proprietary fasteners, or use glue instead of screws, affecting the ability to repair it. Products are often designed in ways that hamper repair, sometimes due to costs/challenges and sometimes intentionally (Cooper and Salvia 2018). There have been some efforts or exploratory work in developing measures of repairability so that consumers can identify repairable models. For instance, iFixit provides a repairability score for a selection of products (e.g., smartphones, laptops, and tablets). Another example is the implementation of a repairability index in France on January 1st, 2021, which requires mandatory display of information on the repairability of electrical and electronic equipment (Ventere et al. 2021; Microsoft 2022). The index includes five criteria: documentation, disassembly, availability of spare parts, price of spare parts, and product-specific aspects. The European Union has also explored the possibility of a scoring system for repair and upgrades of products (Cordella et al. 2019). Meanwhile, the market for phone repair has grown in recent years to $4 billion (IbisWorld 2021).

The challenges related to producing long lasting products along with reusing and repairing them results in at least two needs. The first is the need to be able to differentiate product brand and models by life-expectancy. This might be achieved with a standard metric for measuring life-expectancy, such as an index or score. This would allow consumers to reliably choose longer lasting products if they want them and would allow manufacturers to benefit from producing longer lasting products. Solving this need is also likely to have a significant impact, as there are direct benefits to producers and consumers. Without the ability to differentiate products by life-expectancy, it will likely be difficult to increase the average life-expectancy of a product category. The second need is to be able to differentiate products by repairability. Similarly, this might be achieved with a standard metric for measuring the ability to repair a product, such as an index or score. This would allow consumers to reliably select products that they can repair and allow manufacturers to benefit from producing repairable products. Again, without the ability to differentiate, it will be difficult to increase the repairability of a product category.

5. Recycling and Reducing Consumption

The success of recycling relies on both the user recycling old products and manufacturers utilizing the recycled material. Thus, it requires action from multiple stakeholders. It is estimated that if we recycled all plastics it would result in a 25 % decrease in carbon equivalent emissions (Zheng and Suh 2019). However, the accounts from those within the recycling industry suggest opportunities for further decreasing the impact of the recycling process for some materials. For instance, Minter (2015), which is authored by a journalist with personal experience in the scrap industry, describes several instances where health, safety, and environmental impacts of the recycling process are quite objectionable, including open burning of plastics and little to no protective equipment when handling hazardous materials. Currently, it is estimated that 8.7 % of plastics are recycled (U.S. Environmental Protection Agency 2021). For ferrous metals, an estimated 58 % (H&C Metals 2022) to 73 % (Broadbent 2016) of carbon equivalent emissions are reduced when recycled and an estimated 33 % of these materials are recycled (EPA 2021). It is important to note that recycling consumes energy, sometimes more than that required to produce items from raw material (e.g., glass); thus, it may not always be advantageous to recycle (Chicago Metropolitan Agency for Planning 2013).

There are a number of different materials that might be recycled, as seen in Figure 5.1. The generation and discarding of these materials have varying effects. Each material has a different environmental impact, level of contamination when discarded, technological importance, and raw material abundance. This report will focus primarily on the recycling of metals and plastics. These materials are a nonrenewable resource that often contaminate the environment when discarded; constitute a significant amount of the material in technology products, including electronics, automobiles, and appliances; are in a variety of product types such as clothing (e.g., 52 % of the materials used are polyester made with PET plastic [Textile Exchange 2021]); and they are often recycled at

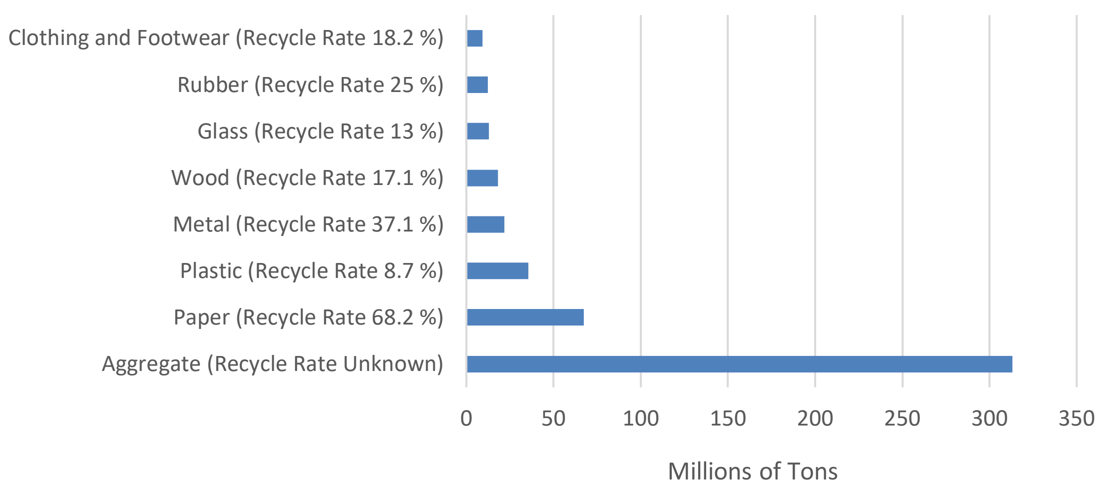


Figure 5.1: Material Generated and Recycle Rate

Source: EPA. (2021c). "Facts and Figures about Materials, Waste and Recycling." https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/z-directory-facts-and-figures-report-about (accessed 7-26-22) a low rate. Other materials are renewable (e.g., wood or cotton), often occur in abundance (e.g., aggregate), do not significantly contaminate the environment when discarded (e.g., glass), are recycled at higher rates (e.g., paper), or play a limited role in technology products.

Jaeger and Upadhyay (2019) conducted a literature review and ten case studies to identify barriers to the adoption of a circular economy in Norway. The results identified seven primary barriers:

- High start-up costs;
- Complex supply chains;
- Challenging business-to-business (B2B) cooperation;
- Lack of information on product design and production;
- Lack of technical skills;
- Quality compromise;
- Disassembly of products is time-consuming and expensive.

In a comparison of 34 countries, the U.S. is below the 50th percentile in its recycling rate, as illustrated in Table 5.1. Many of the higher recycle rates are the result of public policies to increase recycling. For instance, South Korea has the highest recycling rate, which is achieved in part through a twenty-five-cent deposit for single use cups that is refunded when the cup is returned (Belcher 2022). Dumping food waste in landfills was also banned, resulting in a 95 % recycling rate for food waste. Germany, which has the third highest recycling rate in Table 5.1, has a system of fees for packaging along with a more comprehensive collection system (Burran 2021). These efforts contribute to realigning incentives for recycling.

5.1. Metal Recycling

Metals often have a high value and the recycling of metals like copper, aluminum, and steel has been common before public policies on recycling were enacted (Soderholm and Ekvall 2020). Generally, metal can be recycled repeatedly without degradation of the material. Prices for scrap metal are often volatile and determined by the U.S. market, which is influenced by several factors, including weather patterns and shipping costs (Aylen and Albertson 2006). Despite the relatively high value of scrap metal, 29 % of discarded (i.e., recycled, incinerated, or landfilled) nonferrous metal and 54 % of discarded ferrous metal ends up in a landfill (EPA 2021a, EPA 2021b). In the US, metals are recycled at varying rates: lead (76 %), titanium (60 %) magnesium (52 %), aluminum (51 %), nickel (51 %), iron and steel (47 %), tin (35 %), copper (34 %), and chromium (27 %) (Statista Research Department 2022).

Table 5.1: Municipal Solid Waste Recycling Rates by Country, 2020

Country	Recycle Rate
South Korea	57%
Slovenia	57%
Germany	48%
Australia (2019)	45%
Denmark	36%
Norway	35%
Belgium	35%
Latvia	34%
Italy (2019)	32%
Estonia	30%
Switzerland	30%
Slovakia	29%
Luxembourg	28%
Ireland (2019)	28%
Netherlands	28%
Finland	28%
Lithuania	27%
Poland	27%
United Kingdom	26%
Austria (2019)	26%
United States (2018)	24%
France	23%
Czechia	22%
Hungry	22%
Iceland (2018)	21%
Canada (2018)	20%
Sweden (2019)	20%
Spain	19%
Japan (2019)	19%
Greece	16%
Portugal	13%
Turket	12%
Israel	6%
Costa Rica	3%

Source: Tiseo, Ian. "Global Recycling Rates of Municipal Solid Waste 2020, by select Country. Statista. https://www.statista.com/statistics/1052439/rate-of-msw-recycling-worldwide-by-key-country/

Reck and Graedel (2012) identify that recycling is often limited due to human behaviors, product design, and recycling technologies. They further identify that out of 60 metals, 34 are recycled at a rate of less than 1 %, five are recycled at a rate between 1 % and 25 %, 3 between 25 % and 50 %, and 18 at greater than 50 % with many being just above 50 % (Reck and Graedel 2012). Typically, recycling metals requires significantly less energy, sometimes 10 or 20 times less, but some metal alloys cannot be easily reprocessed to their elemental form and others are essentially impossible (Reck and Graedel 2012). The difficulty in separating alloys emphasizes the need to consider the end of life when designing a product. For most unrecycled metals, it is estimated that a price increase of one or two orders of magnitude might be needed to make them economical (Fizaine 2020). Research suggests that factors such as the concentration of metal in a product has more impact on the recycling rate than the price of metals (Fizaine 2020), which again emphasizes the need to consider product design regarding increasing recycling.

Some action items in NIST Special Publication 1500-204 relate to addressing some of the challenges with recycling metals, including research on materials/composition; material science for the reduction/replacement of rare materials; and AI and robotics to identify, assess, and/or disassemble products. New technologies for processing and separating mixed metals and alloys is another area of opportunity for innovation.

Research suggests that designing products for recyclability is likely an important aspect in increasing recycling. Currently, there is limited ability to distinguish recyclable products from non-recyclable products, especially from the consumers point of view. This makes it difficult for consumers to select recyclable products and difficult to align incentives to design products that have increased recyclability.

Given the challenges with metal recycling, at least three needs are identified. There is a need for a standard metric for comparing recyclability to allow consumers to select those products that might be more sustainable. For instance, an index or score. This would not only allow consumers to reliably select recyclable products, but it would also allow producers to benefit from producing recyclable products. This is the most significant of the needs, as this can provide incentives for stakeholders to solve the other needs. Another need is a low cost means for identifying and separating materials. This could include a number of things, such as standards for indicating what materials are in a product or standards for indicating the location of batteries and capacitors. The last need is a low cost means for reprocessing materials, which might include standards for reducing the material variation within a product or new technologies/innovations for reprocessing.

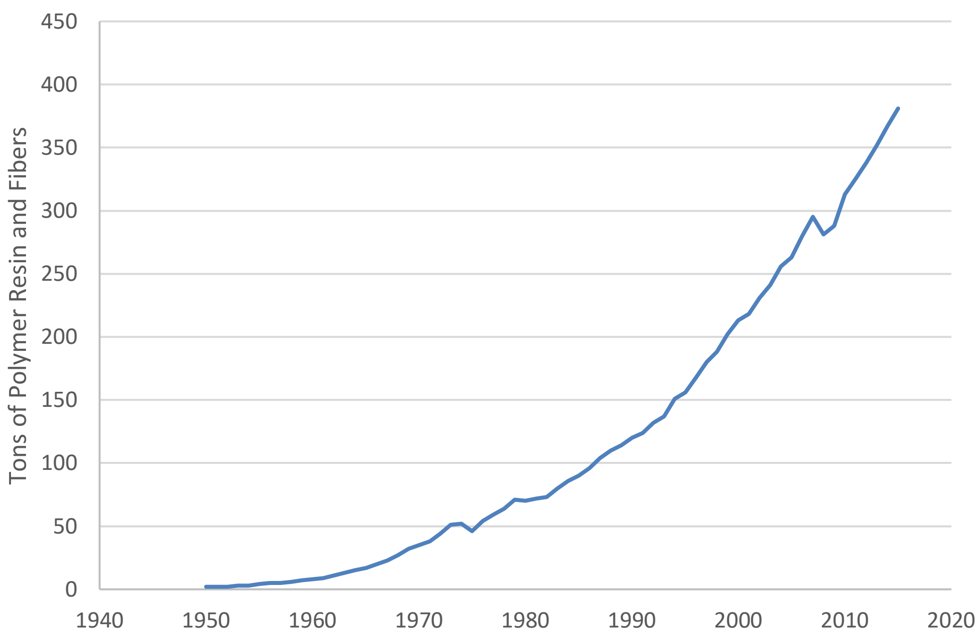
5.2. Plastics Recycling

The adoption and use of plastics increased significantly (see Figure 5.2) in the last 50 years and waste created by this material is becoming increasingly challenging to address. As shown in Table 5.2, polypropylene (PP) represents the largest proportion of resin production with packaging representing the bulk of that production. Low density polyethylene (LDPE) and linear low-density polyethylene (LLDPE) represent the second largest proportion of resin production. The third largest type of plastic is high density polyethylene (HDPE) followed by polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyurethane (PUR), and polystyrene (PS).

Plastic production represents approximately 3.6 % of U.S. environmental impact[1] and was 12.2 % of municipal solid waste in the U.S. in 2018 (U.S. Environmental Protection Agency 2021). There are three primary streams for plastics: landfilling/disposal, recycling, and incineration (Vogt et al. 2021). It is estimated that as of 2015, 9 % of

[1] Calculated using NIST's Manufacturing Cost Guide for 2019 for NAICS 325211, 326110, 326120, 326130, 326140, 326150, 326160, 326190, and 326220 along with the default settings for weighting.

plastic is recycled,12 % is incinerated, and 79 % is disposed of in landfills (Geyer et al. 2017). Globally it is estimated that 16 % of plastics are mechanically recycled, 25 % are incinerated, 40 % are disposed of in landfills, and 19 % are unmanaged (Gao, 2020). PET, which is used for carbonated beverages, has the highest recycle rate (see Table 5.2). Typically, plastic does not biodegrade or does not biodegrade in any reasonable amount of time and plastic debris collects in landfills, waterways, and other locations (Geyer 2017). As previously mentioned, it is estimated that if all plastics were recycled, it would result in a 25 % decrease in carbon equivalent emissions (Zheng and Suh 2019), which is estimated to be 0.9 % of the U.S. economy's environmental impact. It is important to note that despite its environmental impact, plastic often has a lower carbon footprint than other materials (Edwards and Fry 2011; Chaffee and Yaros 2014); thus, there are likely to be tradeoffs when considering an alternative material. There are six primary steps when plastic gets recycled: collection, sorting by plastic type, washing, shredding, separating by quality/class, and finally extruding/compounding, which turns the shredded plastic into pellets that can be used by manufacturers (RTS 2020).



Source: Geyer, Roland, Jambeck, Jenna R., and Law, Kara Lavender. (2017). "Production, use, and fate of all plastics ever made." Science Advances. Vol 3 no. 7. DOI: 10.1126/sciadv.1700782
Source: Ritchie, Hannah and Roser, Max. (2018). "Plastic Pollution." Our World in Data. https://ourworldindata.org/plastic-pollution.

Figure 5.2: Global Plastic Production (million tons)

Table 5.2: Share of Polymer Resin Production According to Polymer Type and Industrial use Sector, 2002-2014

Low Values
High Values

	LDPE, LLDPE (e.g., trash bags, squeeze bottles, flexible films)	**HDPE** (e.g., non-carbonated beverage containers, grocery bags, household cleaner bottles)	**PP** (e.g., straws, cups, ketchup bottles, yogurt containers)	**PS** (e.g., to-go containers, hot cups, utensils, foam packing, trays)	**PVC** (e.g., pipes, windows, synthetic leather)	**PET** (e.g., carbonated beverage bottles, water bottles, heatable food trays)	**PUR**	**Other**	**PP&A Fibers**	**Additives**	**Total**	**Waste Generation (Mt)**
Plastic types	4	2	5	6	3	1		**7**				
Transportation	0.1%	0.8%	2.6%	0.0%	0.3%	0.0%	1.6%	1.4%			6.7%	5.6%
Packaging	13.5%	9.3%	8.2%	2.3%	0.9%	10.1%	0.2%	0.1%			44.8%	46.7%
Building and Construction	1.1%	3.3%	1.2%	2.2%	8.1%	0.0%	2.4%	0.5%			18.8%	4.3%
Electrical/Electronic	0.5%	0.2%	0.9%	0.6%	0.4%	0.0%	0.4%	1.0%			3.8%	4.3%
Consumer and Institutional Products	2.9%	1.7%	3.8%	1.8%	0.6%	0.0%	1.0%	0.2%			11.9%	12.3%
Industrial Machinery	0.2%	0.1%	0.2%	0.0%	0.0%	0.0%	0.3%	0.0%			0.8%	0.3%
Other	1.7%	0.9%	4.2%	0.7%	1.4%	0.0%	2.5%	1.7%			13.2%	12.6%
Textiles	Not broken out separately											13.9%
Total	20.0%	16.3%	21.0%	7.6%	11.8%	10.1%	8.2%	4.9%			100.0%	
Waste Generation (Mt)	18.9%	13.2%	18.2%	5.6%	5.0%	10.6%	5.3%	3.6%	13.9%	5.6%		100.0%
Recycle Rate	5.3%	10.3%	<1	5.3%	<1	19.5%		<1				

NOTE: A grey box means the value is unknown or not broken out separately.
Sources: Geyer (2017), Merrington (2017), Drahl (2020)

Recycled plastic tends to have a lower carbon footprint than virgin material. For instance, an examination of PET, HDPE, and PP showed that for these plastics recycling had a lower carbon footprint than virgin material (Association of Plastic Recyclers 2020). Unfortunately, plastic recycling faces several challenges. For instance, contamination is a concern that can affect performance, appearance, and have health consequences when used in food containers (Selke 2001). Often times recycled material is mixed with virgin material for performance purposes (Selke 2001) and depending on the method for recycling (mechanical vs. chemical), there are some limitations on how many times a plastic can be recycled – typically only 2 to 3 times mechanically (Vogt et al. 2021; Sedaghat 2018). Many consumers may imagine that their soda bottle is recycled repeatedly in a circular flow; however, when a plastic is recycled, it is often recycled for a different use that has lower performance requirements, as recycled plastic typically degrades. For instance, Polyethylene terephthalate (PET) soft drink bottles, which have a higher recycling rate (see Table 5.2) is often recycled into carpet or non-food bottles, as the process for making it suitable as a soda bottle can be expensive (Selke 2001). High density polyethylene (HDPE) bottles, which are often used for non-carbonated beverage containers, is often recycled into drainage pipes, containers, pallets, and lumber (Selke 2001).

Future developments in chemical recycling might allow materials to be recycled many more times than mechanical recycling allows; however, it is a newer process where the costs and environmental impacts are not fully understood. Moreover, the economic and environmental viability of chemical recycling of plastic at large scales is yet to be determined. A survey of literature in Nikiema and Asiedu (2022) estimates the investment cost for processing one ton per day of material using mechanical recycling as being between \$2000 and \$10 000 while that of chemical recycling was estimated at \$857 000 using pyrolysis and \$385 000 using gasification; however, these costs may change as the technology for chemical recycling matures. Note that there is at least one other method for chemical recycling, which uses solvents. Some chemical recycling turns the material into fuel while others can turn the material back into usable plastic. Currently, the EPA does not include chemical recycling in its estimate of the amount of plastic that is recycled (Kaufman 2022) and, under the Clean Air Act, pyrolysis and gasification are classified as waste combustion (Quinn 2022); however, that may change with the development of new technologies. Currently, however, 100 % circularity, in the sense that plastic is regenerated into new products indefinitely, is not feasible with the more prevalent recycling processes (i.e., mechanical recycling), but again this could change with advancements in some forms of chemical recycling.

In addition to the limitations on recycling, there are about 60 popular plastic types with more than 300 different types in total and they cannot all be recycled together. There are about seven major categories of plastic and, potentially, many small streams with a low volume (Chen 2021). Frequently, plastics labeled with the same number cannot necessarily be recycled together. Plastics also contain plasticizers, flame retardants, heat stabilizers, fillers and other additives, which affects the ability to recycle the materials into certain products with specific applications, such as food or biomedical packaging (Gu et al. 2017; Geyer et al. 2017). The result of all these complexities is that the cost for using recycled plastic material for some applications can often be higher than virgin material. In some cases, for manufacturers it is estimated to be slightly higher (see Table

5.3) while in others it can be twice as high as virgin material (Staub 2021). A report prepared by RRS estimates that the marginal cost of incorporating post-consumer recycled plastic into a selection of products was between $0.05 and $0.24 per kg with the primary driver for cost being the application, resin type, and whether the final product will be in contact with food (RRS 2021). Although it is beyond the scope of this report, it is important to note that there are many taxes, subsidies, and other policies both nationally and internationally that affect the price of recycled and virgin plastic. Changing these policies is a tool that can change prices and recycling rates.

Table 5.3: HDPE Plastic Resin Price per Pound

	PCR: Color HDPE (color sorted)	PCR: Color HDPE	PCR: Natural HPDE	PCR: Natural HPDE (food grade)	Virgin HDPE (Spot price)
Cost to source bales or virgin pellets	$0.25	$0.20	$0.20	$0.25	
Handling and transport	$0.16	$0.16	$0.16	$0.16	
Processing and yield loss	$0.14	$0.14	$0.22	$0.22	$0.51
Total	$0.55	$0.50	$0.58	$0.63	$0.51

Resource Recycling. (2019). "Data Corner: What Accounts for the Higher Cost of PCR." https://resource-recycling.com/recycling/2019/08/19/data-corner-what-accounts-for-the-higher-cost-of-pcr/

In considering investments in recycling, it is important to identify the goals that are being pursued, as other solutions might be more effective and/or more economical. For instance, recycling is often discussed hand-in-hand with plastics in the ocean; however, recycling in the U.S. may or may not have a significant impact on this problem. Improved handling of waste materials may have a larger impact along with policies regarding the trade and export of waste. The U.S. is not a major direct contributor to ocean plastic, as it accounts for 0.25 % of the plastics in the ocean (Our World in Data 2021); although, it might be higher when considering indirect contributions. For this reason, the handling of plastic solid waste may have a more significant impact.

Successful recycling tends to happen when it is financially viable, technically feasible, and environmentally safe. Currently, this includes homogeneous high-value, low-contamination streams with many being affected by the price of oil (Merrington 2017). Plastics recycling is often broken into post-industrial recycling and post-consumer recycling. Postindustrial recycling includes recycling waste material generated from the manufacturing process. Many companies focus on this type of recycling, which is often more profitable, as it includes concentrated quantities of uniform material that is, largely, uncontaminated. Postconsumer recycling is the recycling of waste material from consumers. Successful recycling of postconsumer plastics is focused on those available in high volumes, are easily identified, and are of high-value resin type. Unfortunately, only a limited number of plastics present a "value generating" or profitable opportunity. For instance, Gao (2020) identified that approximately 20 % of plastic collection efforts met a threshold 15 % return on investment or higher for recycling (Gao 2020). Another 50 % had positive returns but did not meet the 15 % threshold. The last 30 % had negative returns.

It is important to note that just because a plastic is collected in a recycling effort, does not mean it is recycled, as there needs to be a customer for that material. Some collection efforts for recycling result in plastics being landfilled. A primary source of the economic challenge is that the raw material used to make plastic (e.g., oil) is, generally, a concentrated resource drawn from wells in a limited number of locations. This resource is combined with other materials (e.g., additives or metals), turned into products, and sold globally. To recycle plastic, these same materials need to be recollected, separated, concentrated, and decontaminated, which is a costly process.

NIST Special Publication 1500-204 identifies some action items that relate to making recycling or electronic items more cost effective, including conducting research on purity tolerances for post-consumer feedstocks; rapid material composition fingerprinting; publicity of product materials/composition; and AI and robotics to identify, assess, and/or disassemble products. However, it is going to be difficult, even unlikely, for recycled plastic to be as cost effective as using virgin materials, which are generally uncontaminated and concentrated. For this reason, successful recycling is likely to require more than reducing the costs of recycling. It will likely also require harnessing the consumers' willingness to pay for products made with recycled material.

At the basic level, there is a disconnect in the incentives for recycling plastic material in that the producers and users of plastic products do not bear the cost of the environmental impact for producing and discarding the goods. Additionally, if a manufacturer opts to purchase recycled material at a higher price to be environmentally sustainable, they are likely to struggle to reap benefits for doing so. Only a proportion of consumers are willing to spend more for environmentally friendly products, assuming they can differentiate them from other products. Because of higher material cost, the price of the finished product is likely to be higher, possibly resulting in lost sales. The effect could even be such that it eventually drives the manufacturer out of business, leaving only those producers that did not use recycled material. Moreover, the lack of recycling might be seen as the result of system level failures.

Solutions to facilitating high recycling rates will likely need to address misaligned incentives by either decreasing the costs of using recycled plastic (e.g., through technology solutions, standards, or subsidies), increasing the cost of virgin plastic (e.g., taxes), mandating recycling and the use of recycled material, or realigning incentives. A partial solution that could naturally present itself is that prices of virgin resins increase/decrease with the price of oil (Issifu 2021); thus, if oil prices increase, recycling will likely increase. To put this relationship in context, Weinhagen (2006) estimated that an 8.2 % increase in oil prices results in a 0.6 % increase in plastics prices after 14 months. However, given the economic challenges to plastics recycling, realigning incentives may not be enough. Creating higher volume streams with few contaminants is a critical component of plastics recycling. Thus, more uniform plastic materials and/or low-cost methods for separating contaminants and additives may have a significant impact.

Three primary needs are identified for plastics recycling. The first is a need to aggregate streams to increase volume and economies of scale. This might include reducing the number of plastic types, standards for additives in plastic, standards for tracking additives in plastic, and understanding the economics of individual plastic streams. Another need is standards or technologies for a low cost means for separating post-consumer plastic types and preventing/removing contaminants. The final need is the most notable, which is the need to be able to differentiate product brands and models by recyclability. This might be achieved with a standard metric such as an index or score, which allows consumers to reliably select recyclable products and allow producers to benefit from producing recyclable products. This need is the most notable because it can create incentives for stakeholders to solve the other needs themselves. Aside from regulations, taxes, subsidies, or a substantial increase in virgin material costs, it will likely be difficult to increase plastic recycling rates without the ability to differentiate products by recyclability.

5.3. Reduced Consumption of Materials and Energy

Extending the useful life of products and recycling are significant means for increasing sustainability; however, reducing consumption can also have significant impacts. As shown in Table 5.4, fuels for transportation along with utilities account for 42.7 % of the impact of U.S. household consumption. Some of this is from domestic economic activity and some is imported. Reducing these impacts requires reducing consumption either through efficiency, innovation, or giving up some items.

Manufacturers already invest in material and energy reduction. For instance, there are a number of books and articles on lean manufacturing, Six Sigma, and other continuous improvement efforts for manufacturing such as, “The Toyota Way” (Liker 2004). Manufacturers do have some incentive to reduce their waste, as it results in cost savings; however, the incentives likely do not match the loss from environmental impacts. Moreover, despite the investment that manufacturers make to reduce material and energy, it is likely less than that needed for an efficient outcome.

In regard to household consumption, cultural solutions to reduce consumption of materials and energy could include social pressure on individuals through public messages. For instance, 62 % of respondents in communities that strongly encourage recycling of electronics reported recycling them most or some of the time (Desilver 2016). For those that said their community does not encourage it, only 15 % reported recycling them most or some of the time (Desilver 2016). Prices also affect consumer consumption; thus, increasing energy and material prices are likely to reduce consumption of high resource products and services.

Standards are needed that allow consumers and producers to differentiate products by their efficiency performance. Standards that measure how much energy a product will consume, required maintenance, repairability, durability, and life-expectancy. Without these metrics consumers and producers cannot make informed decisions and the price of the product is likely to disproportionately drive the decision process, as the other factors cannot be accurately measured.

Table 5.4: Carbon Footprint of U.S. Household Consumption (Percent), 2009

	Domestic	Imported	Total
Food	16.7	20.7	17.4
Food at home	12.4	17.4	13.3
Food away from home	4.3	3.4	4.1
Housing	33.6	34.7	33.8
Shelter	2.4	1.9	2.3
Utility	25.0	9.2	22.2
Electronic/Machinery products	0.1	6.3	1.2
Furnishings and supplies	3.4	11.3	4.8
Miscellaneous goods	2.1	5.9	2.8
Clothing	0.0	12.1	2.1
Transportation	29.8	17.1	27.6
Vehicle purchase	0.0	0.1	0.0
Fuels	23.1	8.3	20.5
Public transportation	4.8	3.5	4.6
Transportation services	1.5	4.8	2.1
Services	19.3	15.4	18.6
Entertainment	2.8	1.5	2.6
Education	2.3	1.4	2.1
Health	7.0	6.6	6.9
Other Services	7.2	5.9	7.0
Total	100.0	100.0	100.0
Total (Gigaton of carbon dioxide equivalent)	4.47	0.96	5.43

Source: Adapted from Song, Kaihui; Qu, Shen; Taiebat, Morteza; Liang, Sai; Xu, Ming. (2019). "Scale, distribution and variations of global greenhouse gas emissions driven by U.S. households." Environment International. Volume 133, Part A. https://doi.org/10.1016/j.envint.2019.105137

6. Barriers to Addressing Challenges to a Circular Economy

Several challenges were discussed above, including differentiating products by life-expectancy, repairability, and recyclability. There were also discussions regarding the small streams for plastic recycling and separating materials. In addition to these difficulties, there are some overarching challenges to implementing solutions that create a sustainable economy, including incentives for researchers, misunderstandings, and incentives for sustainable behaviors. There are likely other challenges; however, these capture a large amount of them.

6.1. Mismatch of Incentives for Researchers

Although many researchers in manufacturing could generally describe the benefits of their research, they often do not know the level of economic impact or return on investment for their research or research topic, nor is the research selected based on such criteria. It is often selected as a result of qualitative discussions that may or may not include discussions on economic or societal impacts. This is likely due, in part, to the fact that a manufacturing researcher is focused on natural sciences while economic/societal impacts are studied in the social sciences. Selecting high return research that increases competitiveness, security, innovation, and quality of life is a multi-disciplinary effort that requires mapping natural science research to impacts measured in the social sciences.

In addition to the challenge of selecting high return research, there is also a mismatch of incentives for researchers, as they are rewarded for increasingly complex and innovative discoveries or findings published in journal articles. If the best solution to a problem is simple or involves reiterating previously discovered findings, the reward and acknowledgement is often limited. Moreover, the reward for a researcher does not directly align with the highest return on investment for research. This issue is not well studied for many fields, but it is examined regarding health services. For instance, Cassil (2021) states that “Like many disciplines, the field of health services research (HSR) faces an intensifying quandary over academic incentives that reward researchers for generating grant funding and peer-reviewed articles rather than producing research that improves people’s lives.” Chalmers and Glasziou also acknowledge this problem in stating, “An efficient system of research should address health problems of importance to populations and the interventions and outcomes considered important by patients and clinicians. However, public funding of research is correlated only modestly with disease burden, if at all.” A formal review of clinicians’, patients’, and researchers’ priorities revealed that there is very little overlap, suggesting that researchers may not be addressing the largest challenges in healthcare (Oliver and Gray 2006). Further, the Committee to Evaluate the Artificial Heart Program of the National Heart, Lung, and Blood Institute suggested that decisions about funding would benefit from a cost-effectiveness analysis, similar to cost-benefit analysis except the benefits are not in dollar terms.

Although the examinations mentioned above are in relation to healthcare, it is likely that investigations in other fields would reveal similar disparities. Anecdotal observations suggest that there is likely a similar issue with public or industry level manufacturing research, including science and engineering. Frequently, project proposals, descriptions, and proposals for grants do not estimate the impact of the research or have an estimate of the return on investment. Without such analyses, it is unlikely that researchers are identifying the highest impact or highest return research investments, especially given that there are so many different costs (e.g., capital and labor), cost types (e.g., financial, environmental, and health/safety), activities (e.g., manufacturing, transportation, and material extraction), and stakeholders involved (e.g., manufacturers and consumers). To make the highest impact on adopting a circular economy, it is likely that researchers and decision makers will need to change their approach for identifying projects, as there are too many factors involved to use qualitative discussions alone.

6.2. Popular Misunderstandings

Another barrier to addressing challenges to a circular economy are the commonly occurring misunderstandings. There are many beliefs and ideas that are strongly held that are often inconsistent with the evidence available. For instance, some might consider it common knowledge that women are at higher risk of being murdered or randomly attacked (Bonn 2015); however, in the U.S. an estimated 78 % of homicide victims are male (UNODC 2022) and among individuals attacked by a stranger, men account for 62 % of the victims (Bureau of Justice Statistics 2020). Although this does not relate to sustainability, it does demonstrate that even some things that we consider widespread common-sense knowledge turns out to be inaccurate. Additionally, people and organizations often sensationalize information, selecting statistics, data, and/or language that is often more appealing to their audience but does not necessarily represent an accurate depiction of events or reality. For instance, some years ago, there was a movement to persuade companies to use paper cups instead of polystyrene cups based on their environmental impacts; however, the actual benefits of doing so are not so clear, as discussed by Hocking (1991). In another example, Miller (2020) points to five common myths regarding environmental impacts of single-use plastic:

- “Plastic packaging is the largest contributor to the environmental impact of a product
- Plastic has the most environmental impact of all packaging materials
- Reusable products are always better than single-use plastics
- Recycling and composting should be the highest priority
- ‘Zero waste’ efforts that eliminate single-use plastics minimize the environmental impacts of an event.”

Great care needs to be taken in selecting solutions to reduce environmental impact, as there are many factors to consider. A popular solution may not necessarily be the best solution. Even when the best solution is found, there will likely be a need to effectively communicate that solution to others.

6.3. The ‘Me and Now’

Cognitive bias is a systematic pattern of seemingly irrational behavior at times and is quite common among all people. One bias is our tendency to favor individual short-term rewards. The further disconnected the reward is from ourselves and the present time – that is, the further it is from the ‘me and now’ – the less we value it (Ikeda et al. 2010, Bickel et al. 1999, O'Donoghue and Rabin 2015). Therefore, the willingness of individuals to give up resources for the future and greater good of all people is significantly diminished. For this reason, finding sustainability solutions that utilize existing incentives (e.g., product longevity provides an incentive for the consumer while reducing environmental impact), requires smaller changes, and requires changes from fewer people might tend to be more successful.

7. Summary

Unsustainable economies are generally the result of seemingly logical and rational decisions made by individuals and firms from their stakeholder perspective, which often does not align with sustainability because of a misalignment of incentives. Solutions to this problem often alter the economy so that the logical and rational outcome for the individual/firm matches that of society. The purpose of this report is to discuss the economics of facilitating a sustainable economy. The focus is on decisions and reasons why producers and consumers choose unsustainable practices and products and to identify cost effective solutions that alter these decisions or diminish the negative results of them. This report emphasized standards and technologies for facilitating a sustainable economy.

Unsustainable economies develop primarily as a result of a misalignment of incentives where those that bear the costs of increased sustainability do not receive commensurate benefits. Extending the useful life of products is an effective means for reducing environmental impact for durable goods. Three means for extending the use of a product is to design the product to last longer, reusing a product, and repairing a product rather than discarding it. A potential solution to facilitating a longer useful life is to develop a means to differentiate products by life-expectancy and repairability. For example, a standard scoring system could be created for each of these. Differentiating products by life-expectancy and repairability stands out as a solution as it can have a chain reaction that motivates manufacturers and consumers to produce and use longer lasting products. The following needs were identified:

Recycling is an additional avenue for decreasing environmental impact. This report focused on recycling plastics and metals, as they are a limited resource that often contaminate the environment when discarded; constitute a significant amount of the material in technology products, including electronics, automobiles, and appliances; and they are often recycled at a low rate. Only 8.7 % of plastics are recycled and 29 % of nonferrous metal ends up in a landfill as does 54 % of ferrous metal. Out of 60 metal types, 34 are recycled at a rate of less than 1 %.

Plastics have many challenges to meet to facilitate recycling. One challenge is reducing the number of plastic streams or variations in plastic. Both metal and plastic recycling would benefit from design considerations, where the recyclability of a product is considered at the outset of designing it. A major step toward facilitating a more sustainable economy would include the ability for consumers and others to be able to differentiate products by recyclability. For example, a standard scoring system for recyclability. This would aid in motivating manufacturers to design for recyclability, as it could allow them to potentially capture some of the benefits by differentiating their product from others. There is also a need for increasing the economies of scale for recycling plastic, as there are many small streams (i.e., variations in plastic types and additives). Standards for additives in plastic and for tracking them are needed. There is also a need for standards and technologies that facilitate low cost means for separating post-consumer plastic types and preventing/removing contaminants. Metal recycling would also benefit from standards/technologies that facilitate a low cost means for identifying and separating materials along with reducing the material variation in a product. It would also benefit from a standard metric for measuring recyclability.

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Appendix A: Supplemental Explanation of Economic Methods

This appendix utilizes descriptions in NIST Advanced Manufacturing Series 200-5 to discuss methods for conducting an economic assessment.[2]

A.1. Discount Rate

A discount rate is sometimes referred to as a *hurdle rate*, interest rate, cutoff rate, benchmark, or the cost of capital.[3, 4] Many firms have a fixed discount rate for all projects; however, if a project has a higher level of risk, one should use a higher discount rate commensurate with that risk. This is similar to loaning money to someone who has an elevated likelihood of not paying the loan back. Typically, this person is charged a higher interest rate. Selecting a discount rate is, for many, a challenge. It is, typically, greater than or equal to the return on other readily available investment opportunities (e.g., stocks and bonds). It is, essentially, the minimum rate of return that one would need to engage in a particular investment (e.g., 10 % annual return, 12 % annual return, or higher). One method for selecting a discount rate is the weighted-average cost of capital, which is discussed by Brealey et al.[5] If there is uncertainty about selecting a rate, one might also use a range for a discount rate (e.g., 9 % to 12 %) and calculate two or more estimates for the net present value or conduct a Monte Carlo simulation as discussed in Appendix B.

A.2. Adjusting for Inflation

Some costs increase over time. For example, household energy costs increased 7.9 % between 2006 and 2016. The change in prices is tracked by the Bureau of Labor Statistics and provided to the public in two forms: consumer price index and the producer price index. The consumer price index is a "measure of the average change over time in the prices paid by urban consumers for a market basket of consumer goods and services."[6] The Bureau of Labor Statistics (BLS) provides estimates for individual categories (e.g., energy) and an average for all goods. The producer price index is a "family of indexes that measures the average change over time in the selling prices received by domestic producers of goods and services."[7] Thus, the consumer price index is more appropriate for estimating the increase in the cost of goods while the producer price index is more appropriate for estimating the revenue received for a good. Both are provided as an index with a base year equaling 100 allowing one to estimate the increase in price between any two years. For example, the consumer price index for household energy went from 189.286 in 2010 to 193.648 in 2011, which amounts to a 2.2 % increase:

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[2] Thomas, Douglas S. Investment Analysis Methods: A Practitioners Guide to Understanding the Basic Principles for Investment Decisions in Manufacturing. October 2017. https://doi.org/10.6028/NIST.AMS.200-5

[3] Defusco, Richard, Dennis McLeavey, Jerald Pinto, and David Runkle. Quantitative Methods for Investment Analysis. Baltimore, MD: United Book Press, Inc, 2001. 2.

[4] Brealey, Richard and Stewart Myers. Principles of Corporate Finance. 6th ed. New York, NY: McGraw-Hill, 2000. 17.

[5] Brealey, Richard, Stewart Myers, and Franklin Allen. Principles of Corporate Finance. 11th ed. New York, NY: McGraw-Hill, 2014.

[6] Bureau of Labor Statistics. Consumer Price Index. https://www.bls.gov/cpi/

[7] Bureau of Labor Statistics. Producer Price Index. https://www.bls.gov/ppi/

$$2.2\ \% = \left[\left(\frac{193.648}{189.286}\right) - 1\right] * 100\%$$

This value provides some estimate of the increase in prices that might be expected in the future.

A.3. Present Value

A critical concept for evaluating an investment decision is the time value of money; that is, the relationship between cash flows occurring at different time periods. For example, receiving $1000 today is typically preferred to receiving $1000 one year from now. In order to compare these two cash flows occurring at different dates, the future cash flow is *discounted* to equate its value to cash flows received today.[8, 9] This is done by dividing the future cash flow by an interest rate or discount rate:

Equation 1

$$PV_1 = \frac{CF_1}{1 + r}$$

Where
PV_1 = Present value of future cash flow after one year
CF_1 = Cash flow after one year
r = Discount rate which is, typically, between 0 and 1

The discount rate can be illustrated by considering how much one would need to be compensated to loan $1000 to someone for one year. If that value is $100, then the interest rate is 10 %, which is the discount rate. The $1100 dollars that would be received in one year is equivalent to $1000 today when discounted using Equation 1 and the 10 % discount rate.

To calculate present value for cash flows after multiple years, the numerator in Equation 1 is raised to the power of the number of years that have passed:

Equation 2

$$PV_t = \frac{CF_t}{(1 + r)^t}$$

[8] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 61.
[9] Defusco, Richard, Dennis McLeavey, Jerald Pinto, and David Runkle. Quantitative Investment Analysis. Hoboken, NJ: John Wiley and Sons, 2015. 2-3.

Where
PV_t = Present value of future cash flow after number of t years
CF_t = Cash flow in year t
r = Discount rate which is, typically, between 0 and 1

A.4. Net Present Value

Net present value is the difference between the present value of all cash inflows and the present value of all cash outflows over the period of the investment.[10, 11, 12] Net present value, which accounts for the time value of money, is a common metric for examining an investment, and is considered a superior method over other approaches.[13, 14] Other approaches often have caveats, do not consider all cash flows, or do not consider the time value of money. Net present value is calculated by taking each monetary cost and benefit associated with an investment and adjusting it to a common time period, which we will call time zero. The adjustment is for the time value of money, as described above. In addition to the time value of money, there is also the decreased purchase power of money due to inflation. The inflows are summed together and the outflows (costs) are subtracted resulting in the net present value:

Equation 3

$$NPV = -C_0 + I_0 + \frac{-C_1}{(1+r)} + \frac{I_1}{(1+r)} + \frac{-C_2}{(1+r)^2} + \frac{I_2}{(1+r)^2} \cdots \frac{-C_T}{(1+r)^T} + \frac{I_T}{(1+r)^T}$$

Where:
I_t = Total cash inflow in time period t
C_t = Total cost in time period t
r = Discount rate
t = Time period, which is typically measured in years

Or, written another way

[10] Defusco, Richard, Dennis McLeavey, Jerald Pinto, and David Runkle. Quantitative Methods for Investment Analysis. Baltimore, MD: United Book Press, Inc, 2001. 54-56
[11] Budnick, Frank. Applied Mathematics for Business, Economics, and the Social Sciences. New York, NY: McGraw-Hill, 1988. 894-895.
[12] Defusco, Richard, Dennis McLeavey, Jerald Pinto, and David Runkle. Quantitative Investment Analysis. Hoboken, NJ: John Wiley and Sons, 2015. 44-45.
[13] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 223.
[14] Helfert, Erich A. Financial Analysis: Tools and Techniques: A Guide for Managers. New York, NY: McGraw Hill, 2001. 235.

Equation 4

$$NPV = \sum_{t=0}^{T} \frac{(I_t - C_t)}{(1 + r)^t}$$

The net cash inflows for each time period are divided by one plus a selected discount rate raised to the power of the time period, t. One challenge with net present value is determining a discount rate, which was discussed previously. One can select either a nominal or real discount rate, which is determined by whether it is a current or constant dollar analysis. In a current dollar analysis, the costs and benefits are not adjusted for inflation; thus, the discount rate tends to be *higher*. In a constant dollar analysis, the costs and benefits are adjusted to a common year for inflation; therefore, the discount rate is *lower*, as it does not need to account for inflation.

New technologies offer different benefits, including reduced costs or increased revenue. In order to estimate the net present value, it might be necessary to forecast any increased sales to estimate additional revenue due to adopting a new technology. It is important to also include the associated additional costs of production, but only include those costs and benefits associated with the investment. Including costs that would be incurred without the investment in the new technology will negatively skew some of the other measures discussed below.

Interpreting net present value is at times difficult. If net present value is positive, it means that the return on the investment is expected to exceed the discount rate. An anticipated follow-up question is what the rate of return is on the investment. Net present value does not reveal this information. The internal rate of return is more appropriate for answering this question. The net present value, however, can be used to determine whether an investment is economical and to rank investments.

It is important to remember that prices of some goods can change over time at rates different than general inflation. Price escalation occurs when prices increase faster than inflation, while price de-escalation occurs when prices increase slower than inflation (or decline). If an investment has a recurring cost that escalates, then the analysis will need to account for this by having higher cost values for each subsequent time period.

A.5. Internal Rate of Return

Internal rate of return is a widely-used metric for evaluating investments. It has been suggested that in some industries, it is the principal method used for such analyses. The internal rate of return is, essentially, the discount rate at which the net present value is zero. Thus, it is calculated by setting NPV in Equation 4 to equal zero and solving for r.[15, 16] Due to the nature of this calculation, individuals use software or trial and error

[15] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 152-153.
[16] Defusco, Richard, Dennis McLeavey, Jerald Pinto, and David Runkle. Quantitative Methods for Investment Analysis. Baltimore, MD: United Book Press, Inc, 2001. 44-49

to identify the internal rate of return (i.e., select varying discount rates for Equation 4 in order to identify the value where the net present value equals zero).

One of the benefits of using the internal rate of return is that there is no need to select a discount rate. Generally, if the internal rate of return is calculated to be greater than or equal to your minimum required rate of return to make an investment (e.g., discount rate or hurdle rate), then the investment is economic.

Unfortunately, the internal rate of return has some deficiencies. The measure does not reveal the size of the investment. For instance, consider a $1 investment opportunity that has a return of 100 % after one year compared to a $10 000 investment that has a return of 30 % after one year. The first opportunity has a higher rate of return while the second one has a higher dollar return. Net present value reveals this difference while the internal rate of return does not.

The internal rate of return also does not reveal the duration of the investment. It is often preferred to have a long-term investment rather than a short-term investment, all else equal, as it avoids the cost and risk of having to reinvest. After a short-term investment is completed, one has to identify the next investment, which may or may not have a high return. Another challenge occurs when a project generates immediate inflows.[17] For instance, consider an investment that has an initial cost of $1000 and generates $1200 after the first year compared to one that immediately generates $1000 and has a cost of $1200 after the first year. Both have an internal rate of return of 20 %; however, using a 5 % discount rate, the net present value of the first case is $143 whereas the second one is $-143. In this instance, the net present value is the better choice for analysis.

Another situation where the internal rate of return is not a sufficient metric can occur when net cash flows for different time periods flip signs. Consider an example provided by Ross where the initial net cash flow is $-100, $230 after the first year, and $-132 in the third year.[18] There are two internal rates of return with one being 10 % and the other 20 %.[19] In this instance, one must use the net present value to make a sound decision. Moreover, the internal rate of return may be an intuitive metric; however, it should be used along with net present value rather than in place of it.

A.6. Modified Internal Rate of Return

The modified internal rate of return may or may not be a prominent method used for economic decision making; however, given the prominence of the internal rate of return and the many short comings of this metric, it is prudent to discuss the modified internal rate of return. This calculation assumes that cash inflows are reinvested at the rate of return equal to the discount rate.[20, 21] It can be represented as:

[17] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 152-153.
[18] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 146-149.
[19] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 152-153.
[20] Lin, Steven. "The Modified Internal Rate of Return and Investment Criterion." *The Engineering Economist.* 1976. 21(4) 237-247.
[21]

Equation 5

$$MIRR = \sqrt[T]{\frac{\sum_{t=0}^{T}[I_t(1+r)^{T-t}]}{\sum_{t=0}^{T}[C_t/(1+r)^t]}} - 1$$

Where
I_t = Total cash inflow in time period t
C_t = Total cost in time period t
r = Discount rate
t = Time period, which is typically measured in years

This equation is somewhat more complex than the calculation of the internal rate of return, but it avoids many of the downfalls associated with it. As previously mentioned, it is assumed that cash inflows are reinvested, which is why cash inflow I_t is multiplied by $(1+r)^{T-t}$. The cost C_t in the denominator is discounted in a similar fashion to net present value. Moreover, it is the future value of all net incomes divided by the present value of all net costs. The T root of this value, less one, is equal to the modified internal rate of return.

A.7. Payback Period and Discounted Payback Period

Payback period is the time required to recoup the investment without discounting any cash flows.[22] For example, consider an investment that has an initial cost of $25 000 with a net cash inflow of $10 000 after one year, $15 000 after two years, and $12 000 after three years. The payback period is two years, as the sum of $10 000 and $15 000 equals the initial investment of $25 000. The discounted payback period makes the same estimation except the cash flows are discounted.[23] Using the previously mentioned example along with a 10 % discount rate, the payback period would be 3 years or less depending on when the cash flows are received during the year.

Payback period and the discounted payback period are often used for small investment decisions. For example, replacing a conference room's lights with energy efficient bulbs or tuning up a vehicle to save fuel. It is a quick method; however, it has a number of significant drawbacks with one being that it does not consider any future cash flows beyond the payback period. For large investments, this method should be considered a supplement to net present value.

[22] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 146-149.
[23] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 146-149.

A.8. Benefit Cost Ratio

Benefit cost ratio is the present value benefits divided by present value costs. One issue to consider is which items to include as costs. In some cases, investors might include only the initial investment as the cost. Alternatives should be compared over the same study period. A larger benefit cost ratio represents a more economic investment.

A.9. Real Options and Decision Trees

As discussed previously, net present value is considered a superior method over other approaches; however, this method does not consider the possibility of adjusting an investment after it has been initiated. A survey presented by Block indicates that 14 % of Fortune 1000 companies used real options in their economic evaluations.[24] Adjusting for decisions, known as real options, can provide additional value to a project.[25] For instance, if a pilot or prototype product is successful, then there is the option to expand. There is also the option to abandon it in the case that it is not successful. Another example can be found in comparing two projects with the same net present value. Consider a project that commits to a technology that cannot be changed for many years compared to one with the same net present value, but there is no commitment to any particular technology. The second project is preferred over the first, as it allows for options. Moreover, real options suggests that the total value of a project is the net present value plus the value of options:

Equation 6

$$TPV = NPV + VO$$

Where
TPV = Total project value
NPV = Net present value from Equation 3 and Equation 4
VO = Value of options

A great deal of the literature on real options focuses on well-defined financial options, which do not always transfer well into project investment.[26] Options pricing theory is an advanced topic, which is not completely covered in this document. For more information, one might consult Copeland and Antikarov or Brealey and Meyers.[27, 28]

Although real options pricing is not fully discussed here, it can be described in a decision tree. There are, typically, three types of nodes in a decision tree:

[24] Block, Stanley. "Are Real Options; Actually Used in the Real World?" The Engineering Economist. 2007 52(3) 255-267.
[25] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. Corporate Finance. New York, NY: McGraw-Hill, 2005. 223.
[26] Van Putten, Alexander and Ian MacMillan. "Making Real Options Really Work." Harvard Business Review. December 2004. https://hbr.org/2004/12/making-real-options-really-work
[27] Brealey, Richard and Stewart Myers. Principles of Corporate Finance. 6th ed. New York, NY: McGraw-Hill, 2000. 583-666
[28] Copeland, Tom and Vladimir Antikarov. Real Options: A Practitioner's Guide. United Kingdom: Thompson Corporation, 2003.

Decision nodes represented by squares,
Chance nodes represented by circles, and
End nodes represented by triangles

An example is provided in Figure A.1, which presents an investment with an initial cost of $15 million. It has a probability of 0.8 that it results in $5 million cash inflow after one year and has the option to expand at a cost of $2 million, resulting in an additional $30 million cash inflow in after two years. Alternatively, there is a 0.2 probability of a cash inflow of $1 million with the option to terminate the project at a cost of $1 million, resulting in an additional cash inflow of $6 million in year two. This investment has four possible net present values, as seen in Figure A.1. Since an investor would choose the highest net present value, we can eliminate those options that would not be chosen (i.e., the second and fourth net present values). We can then calculate the expected net present value by calculating the net present value for the branch with the probability of 0.8 which is

$$\frac{\$5\ million}{1.07} - \frac{\$2\ million}{1.07^2} + \frac{\$30\ million}{1.07^2} = \$29.0\ million$$

We can then calculate the expected net present value for the branch with the probability of 0.2, which is

$$\frac{\$1\ million}{1.07} - \frac{\$1\ million}{1.07^2} + \frac{\$6\ million}{1.07^2} = \$5.2\ million$$

Finally, we can multiply these by their respective probabilities and add the initial cost:

$$0.8 * \$29.0\ million + 0.2 * \$5.2\ million - \$15\ million = \$9.3\ million$$

The expected value of the investment without the options (i.e., no option to expand and no option to terminate) is -$1.5 million; thus, the options add $10.7 million to the net present value of the investment (i.e., the difference between $9.3 million and -$1.5 million before rounding).

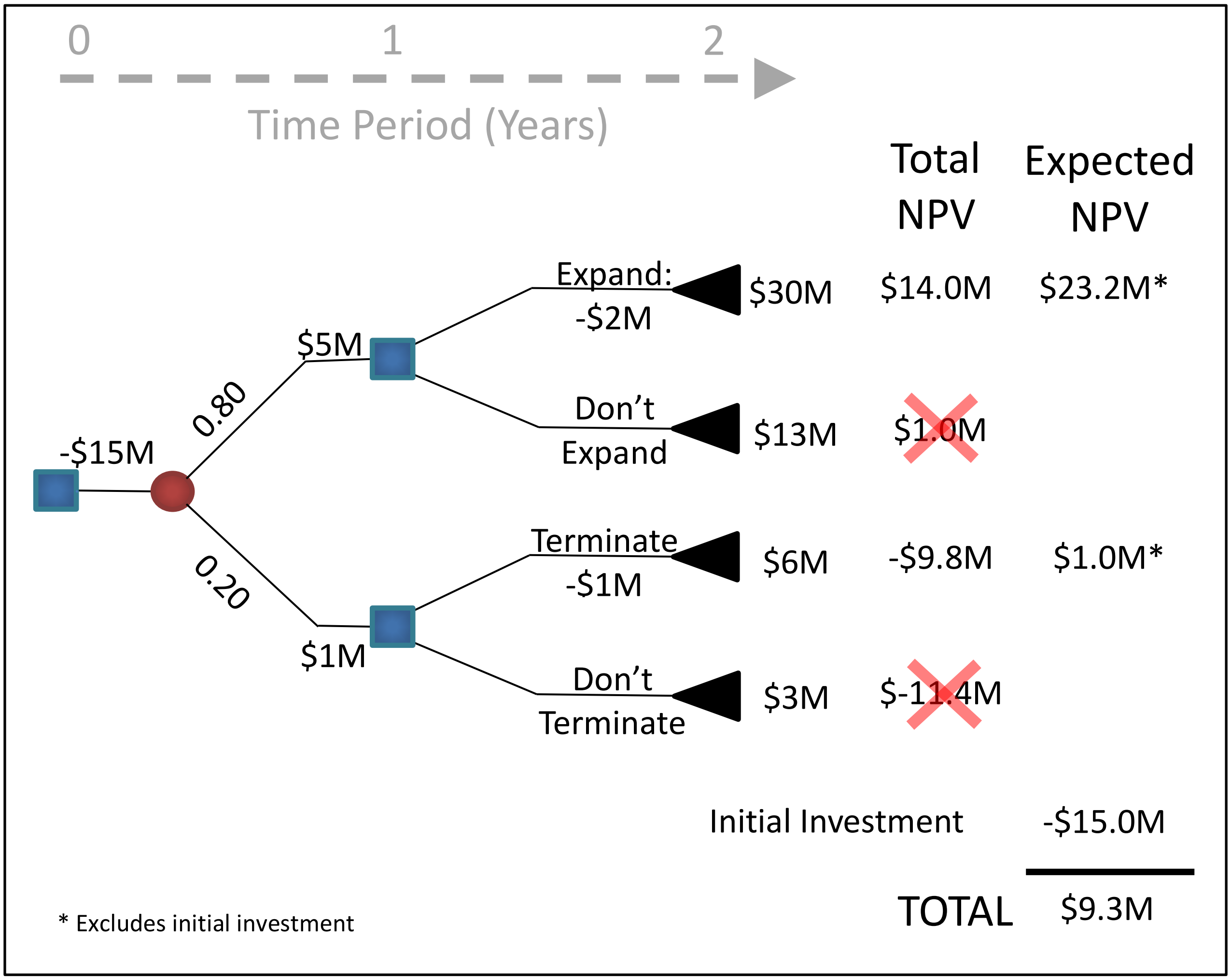

Figure A. 1: Example of a Decision Tree using a 7 % Discount Rate

Rather than calculating the expected value, one might use a Monte Carlo analysis, as described in Appendix B. This is particularly useful in the event that there are multiple chance nodes.

A.10. Adjusted Present Value

Adjusted present value is described as the net present value plus the net present value of financing and the effects of financing.[29] This includes subsidies to debt, cost of issuing new securities, cost of financial distress, or other costs/benefits of financing. It is, generally, assumed that financing occurs solely through equity:

[29] Brealey, Richard and Stewart Myers. Principles of Corporate Finance. 6th ed. New York, NY: McGraw-Hill, 2000. 555-557.

Equation 7

$$APV = NPV + EF$$

Where
APV = Adjusted present value
NPV = Net present value from Equation 3 and Equation 4
EF = Effects of financing (e.g., interest on a loan)

An example of the effects of financing might include a company that, in order to invest, has to issue stock, where doing so comes with costs for underwriting, lawyers, and others involved in the transaction.

Appendix B: Supplemental Information for Dealing with Uncertainty

In addition to the methods presented in Appendix A, one often needs to consider uncertainty in data estimates. This appendix utilizes descriptions in NIST Advanced Manufacturing Series 200-5 to discuss methods for conducting an economic assessment incorporating sensitivity analysis.[30]

To account for uncertainty, a probabilistic sensitivity analysis can be conducted using Monte Carlo methods. This technique is based on works by McKay, Conover, and Beckman[31] and by Harris[32] that involves a method of model sampling. It can be implemented using various software packages such as the Crystal Ball software product[33] or the Cost Effectiveness Tool provided by NIST.

Specification involves defining which variables are to be simulated, the distribution of each of these variables, and the number of iterations performed. The software then randomly samples from the probabilities for each input variable of interest. Three common distributions that are used include triangular, normal, and uniform. To illustrate, consider a situation where a firm has to purchase 100 ball bearings at \$10 each; however, the price can vary plus or minus \$2. In order to address this situation, one can use a Monte Carlo analysis where the price is varied using a triangular distribution with \$12 being the maximum, \$8 being the minimum, and \$10 being the most likely. Moreover, the anticipated results should have a low value of approximately \$800 (i.e., 100 ball bearings at \$8 each) and a high value of approximately \$1200 (i.e., 100 ball bearings at \$12 each). The triangular distribution would make it so the \$8 price and \$12 price have lower likelihoods.

For a Monte Carlo analysis, one also must select the number of iterations that the simulation will run. Each iteration is similar to rolling a pair of dice, albeit, with the probabilities having been altered. In this case, the dice determine the price of the bearings. The number of iterations is the number of times this simulation is calculated. For this example, ten thousand iterations were selected and a simulation was ran using Oracle's Crystal Ball software. The frequency graph shown in Figure B.1 shows the number of times each value was created. Since a triangular distribution was selected, the far left and far right values are less likely to be selected while the most likely value is in the middle at approximately \$1000 (i.e., 100 bearings at \$10 each). The sum of all the bars in the graph is a probability of 1.0 with a total frequency of 10 000. Instead of a triangular distribution, a uniform distribution could have been selected where each value between \$8 and \$12 has an equal chance of being selected in each iteration. The results from such a distribution are shown in Figure B.2.

[30] Thomas, Douglas S. Investment Analysis Methods: A Practitioners Guide to Understanding the Basic Principles for Investment Decisions in Manufacturing. October 2017. https://doi.org/10.6028/NIST.AMS.200-5
[31] McKay, M. C., Conover, W. H., and Beckman, R.J. "A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code," Technometrics 21 (1979): 239-245.
[32] Harris, C. M. Issues in Sensitivity and Statistical Analysis of Large-Scale, Computer-Based Models, NBS GCR 84-466, Gaithersburg, MD: National Bureau of Standards, 1984.
[33] Oracle. Crystal Ball, Crystal Ball 11.1.2.3 User Manual. Denver, CO: Decisioneering, Inc, 2013.

The benefit of Monte Carlo analysis is in the situation where there are many variables that can fluctuate (e.g., price of energy, materials, and labor). Instead of having just one price fluctuating, maybe a dozen prices fluctuate.

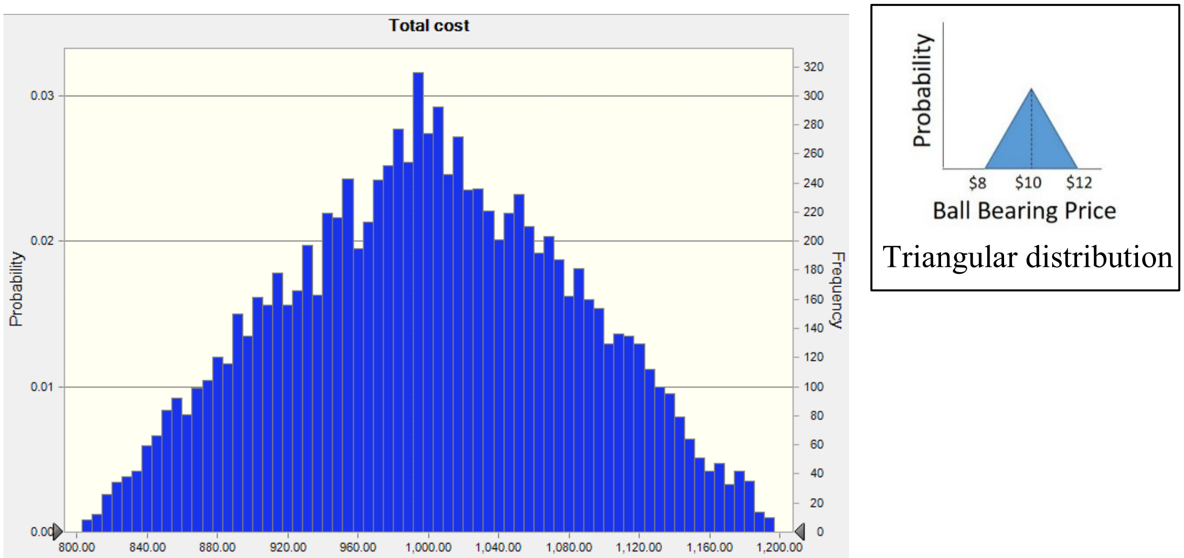

Figure B. 1: Frequency Graph of the Total Cost for Ball Bearing Example using a Triangular Distribution

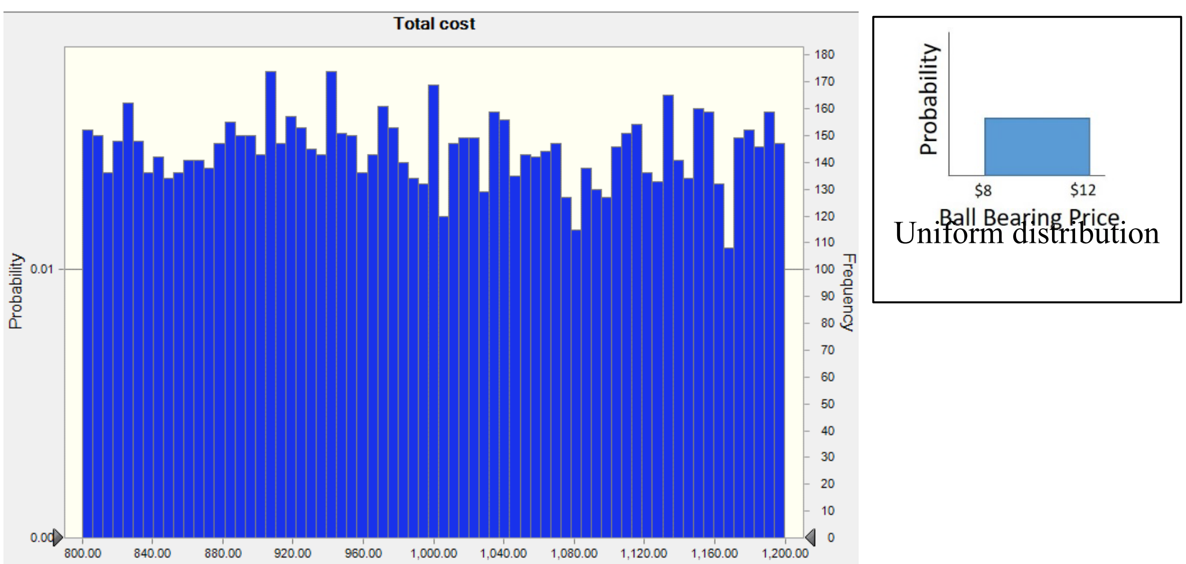

Figure B. 2: Frequency Graph of the Total Cost for Ball Bearing Example using a Uniform Distribution

Appendix C: The Analytical Hierarchy Process

The analytic hierarchy process (AHP) is a technique developed by Saaty (1980)[34] to assist in decision-making when dealing with multi-attribute criteria. It uses pairwise comparisons as the fundamental analytical tool in its decision-making process. Since its introduction, the technique has been used in a range of fields from risk assessment for petroleum transport to choosing professors at a university. Due to the complicated, multi-step process that many manufacturers face when dealing with a range of issues from selecting a product to manufacture to choosing among a slew of investments in various manufacturing operations, AHP is an ideal tool for dealing with the complex decisions that manufacturers must make.

AHP can be applied to prioritization, ranking, and benchmarking situations. It can also be utilized for resource allocation and quality management decision-making. The range of possible applications of AHP means that a manufacturer can use the process for nearly all the complex decision-making choices she faces.

Although AHP can be conducted in several different ways, the core steps remain the same. First, in the case of a manufacturer, the manufacturer must identify all of the possible outcomes/choices at all levels of the decision-making process. Sometimes manufacturers face a decision-making process that is sequential in nature, while other times the decision-making process may require simultaneous choices. All types of decision-making are covered by AHP, but the decision-maker must identify *all* possible ranges of outcomes *before* embarking on the AHP process. If the decision-maker does not identify the full range of possible outcomes at the onset, she would need to repeat the process once the full breadth of options is known so that the process results in the best choice for the decision-maker.

The best way to demonstrate the efficacy of AHP is by working through an example. Let us assume that a manufacturer of prefabricated homes wants to package solar panels along with the homes they are building. There are three possible solar panel vendors that our manufacturer can choose among – vendors A, B, and C. The manufacturer naturally wants to choose the “best” solar panels for its prefabricated homes. But what constitutes the “best” in these circumstances?

Let us further assume that the manufacturer already has a set of *criteria* on what constitutes the “best” for solar panels; namely solar panels that prevail on four different dimensions – cost, aesthetics, solar cell efficiency, and resale value. Note that while some of these criteria can be quantified exactly – like the cost – others, like resale value, rely on future market conditions that can only be imprecisely known and therefore must be estimated. The fact that some criteria are exactly known and that others must be estimated does not stop the manufacturer from conducting the AHP analysis however.

What is also important to note is that some of these criteria may be subdivided into ¬sub-criteria. For the sake of our example, we will also assume that solar cell efficiency can be further divided into two sub-criteria -- thermodynamic and quantum efficiency. Thus, two of our criteria have sub-criteria and two do not.

[34] Saaty, Thomas L. The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. (McGraw-Hill, 1980).

As Saaty (1980) developed it, AHP relies on the preferences of the person or entity making the decision. Because a manufacturer might be choosing between criteria that are measured on different dimensions – like cost and efficiency – the AHP calculation is invaluable in creating a standard metric that enables the comparison of alternatives.

AHP requires us to use *pairwise comparisons* in making our ultimate decision. In fact, AHP can be thought of as the aggregation of sets of pairwise comparisons. AHP calculations can be accomplished by any number of software packages, but we will walk through the intuition driving those calculations here.

In making the pairwise comparisons, AHP requires that the decision-maker quantifies their preferences on a numerical scale. The widespread convention with AHP is to use a nine-point scale that was first published in *Expert Choice User's Guide*, Decision Support Software, Inc., Pittsburgh, PA, 1993 and which is reprinted on page 275 of the *ASTM Standards on Building Economics, 7th Edition*. That table is reproduced below (see Table C.1).

Table C. 1: AHP Numerical Scale

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to objective
3	Moderate Importance	Slightly favor one activity over another
5	Essential Importance	Strongly favor one activity over another
7	Very Strong Importance	Very strongly favor one activity over another
9	Extreme Importance	Favor one activity over another as strongly as possible
2,4,6,8	Intermediate Values	Compromise between two of the defined values

From this table, we see that the importance of an alternative goes up as one makes the journey up the scale, with nine reflecting a value of "extreme importance." The even numbers in this scheme represent the "intermediate values" between the main AHP intensities. It is this table that is used when developing weights for the preferences. As will be explained below, some inconsistency in the preference weightings is tolerable in AHP.

Now we need to do pairwise comparisons between each of the alternatives, stating which of any two options is the preferred criteria *and* the intensity of that preference. The decision-maker can choose whatever preferences they want and indicate those efficiencies, as long as *relative consistency* is not violated. Consistency here is obtained when the priorities are unique and the preference order of the pairwise comparison matrices is also maintained. AHP allows for some inconsistencies because some cardinal inconsistency is expected when dealing with people ranking choices. However, a good software tool will prevent too much inconsistency from showing up in the AHP model. Saaty crated a measure known as the consistency index (CI) that allows the user to check the consistency of their own preference as part of the larger AHP process. The CI formula is expressed as:

$$CI = (\lambda \max - n)/(n-1)$$

where λ max is the Principal Eigenvalue and n is the dimension of the matrix

The steps for calculating the CI are easy to follow. First one must arrange all of the pairwise comparisons into matrices. Then each column of the pair wise comparison matrix must be multiplied by the corresponding weight. Then we must divide the sum of the row entries by the corresponding weight. Afterwards we average all of the values derived from the previous step. It is this average which is λ max. Knowing that n is the dimension of the matrix, we can now calculate the CI.

The standard practice for AHP is to proceed with the analysis when the CR = 0.1 or a value below that. This allows for some inconsistency in the preferences and means that some violations of transitivity can be allowed.

A good AHP software program will calculate these consistency ratios and not let the decision-maker proceed if even one of these consistency ratios is violated. Below is an example that has been generated where none of the consistency ratios has been violated (see Table C.2).

Table C. 2: Example of AHP Pairwise Comparisons for Solar Panels

		More Important Criteria	Intensity of Importance
Cost	Aesthetics	Cost	7
Cost	Efficiency	Cost	4
Cost	Resale Value	Cost	5
Aesthetics	Efficiency	Efficiency	7
Aesthetics	Resale Value	Resale Value	3
Efficiency	Resale Value	Efficiency	3

Using the software tool, the manufacturer indicates the preferences above between the criteria. However, remember that one of our criteria – solar cell efficiency -- has two sub-criteria. Each of these sub-criteria need to be ranked in a way that does not also violate the consistency ratios.

Because cost, aesthetics and resale value do not have sub-criteria, we can pass over them in the analysis and proceed onto efficiency, which has two sub-criteria – thermodynamic efficiency and quantum efficiency (see Table C.3).

Table C. 3: Example of AHP Comparison of Sub-Criteria for Solar Panels

		Most Important Criteria	Intensity of Importance
Thermodynamic Efficiency	Quantum Efficiency	Thermodynamic Efficiency	5

We can now calculate the geometric means and weights for the cost sub-criteria (see Table C.4). Unlike the traditional arithmetic mean, which is calculated by summing the data points and then dividing by the number of observations, the geometric mean is calculated by taking the product of all the observations in the data set and then taking the *nth* root of that product where *n* is the number of observations in the data. For example, if we have ten observations and want to take the geometric mean, we multiply the ten observations and then take the 10^{th} root of that resulting product.

Table C. 4: AHP Example of Geometric Mean, Weight, and Consistency Measure for Solar Panel Sub-Criteria

	Geometric Mean	Weight	Consistency Measure
Thermodynamic Efficiency	2.24	0.83	2
Quantum Efficiency	0.45	0.17	2
Total Geometric Mean	2.68		

Now that we have calculated the sub-criteria geometric means, while maintaining the consistency ratios, we can calculate the *criteria* geometric means. Remember that our four criteria have been ranked against each other and can be depicted, in relation to each other, by the following table.

Table C. 5: Example of AHP Pairwise Comparison Matrix for Solar Panels

	Cost	Aesthetics	Efficiency	Resale Value
Cost	1	7	4	5
Aesthetics	0.14	1	0.14	0.33
Efficiency	0.25	7	1	3
Resale Value	0.2	3	0.33	1

We can now calculate the geometric means and weights for the criteria (see Table C.6).

Table C. 6: Example of Geometric Mean, Weight, and Consistency Measure for Solar Panels

	Geometric Mean	Weight	Consistency Measure
Cost	3.44	0.58	4.32
Aesthetics	0.29	0.05	4.24
Efficiency	1.51	0.26	4.22
Resale Value	0.67	0.11	4.07

The results, with both criteria and sub-criteria, can be summarized here (see Table C.7):

Table C. 7: Example of AHP Weighting for Solar Panels

Criteria	Criteria Weight	Sub-Criteria	Sub-Criteria Weight	Global Priorities
Cost	0.58			58.2 %
Aesthetics	0.05			4.9 %
Efficiency	0.26	Thermodynamic Efficiency	0.83	21.3 %
Efficiency	0.26	Quantum Efficiency	0.17	4.3 %
Resale Value	0.11			11.3 %

In this hypothetical example, we now know that the manufacturers rank cost most importantly, followed by efficiency, followed by resale value, with aesthetics in last place. The weights are determined by the decision-maker's preferences and reveal the relative magnitude of importance for each criteria (i.e., cost, aesthetics, efficiency, and resale value); thus, the weights can then be used to create a single score that can be utilized to compare each option (not shown), such as choosing among solar panels. With these preferences quantified in this manner, the decision-maker can choose the option that AHP points her towards and show parties outside the decision-making process just how her decisions were made in a rigorous manner.

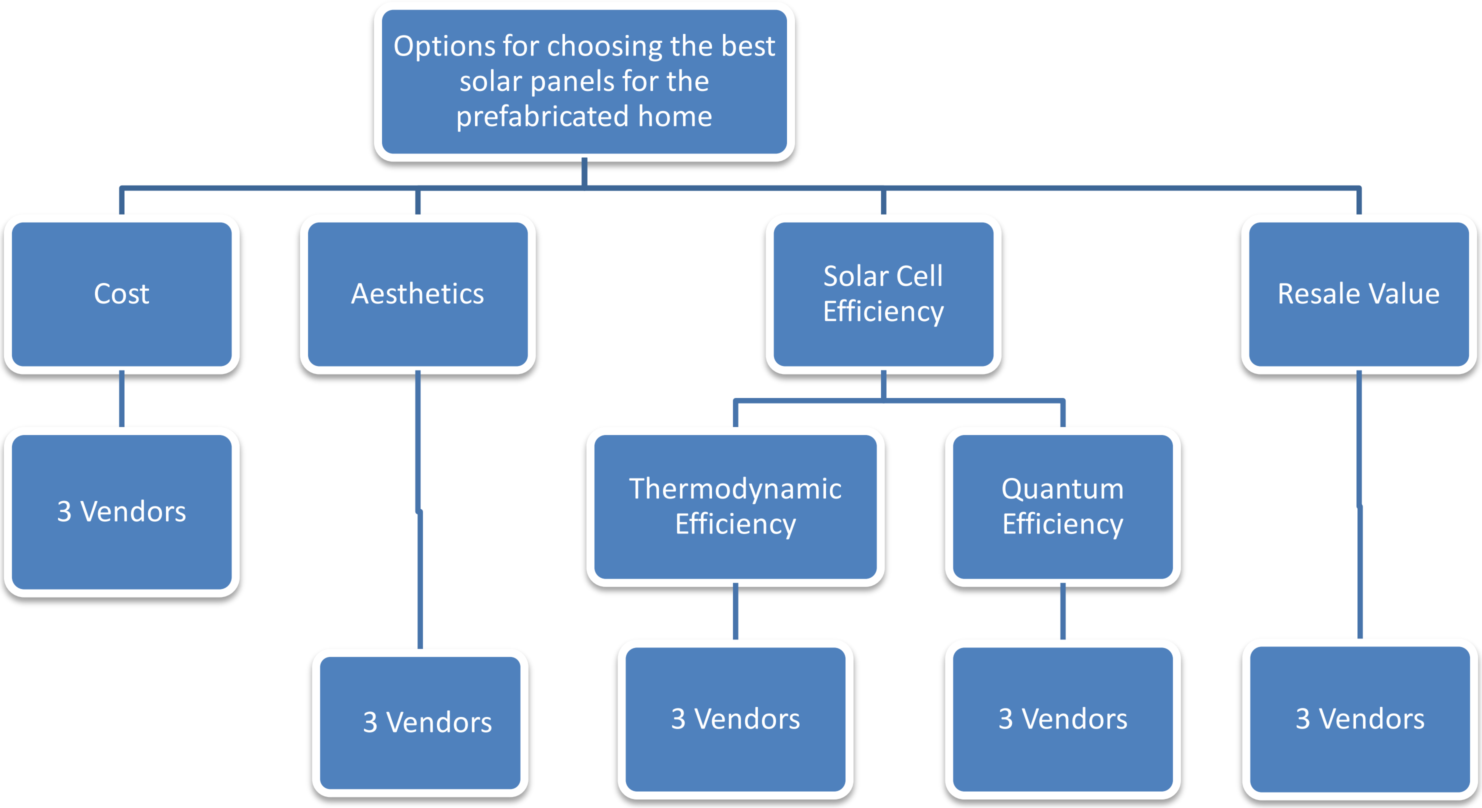

Figure C. 1: Illustration of AHP Criteria and Sub-Criteria