Building For A Greener Future

Albert Park, Cassandra Trickett, Dane Worley, Jamie Tian, Julie Kelleher, Riley Cutner, &

Tinny Cheung

Advisor: Deepak Rajagopal

Client: Gensler

UCLA Institute of the Environment & Sustainability

La Kretz Hall, Suite 300 • Box 951496 • Los Angeles, CA 90095-1496

Practicum in Environmental Science

June 2013

TABLE OF CONTENTS

1. Executive Summary

While much progress has been made in improving energy efficiency and consumption habits, many people are unaware that the choices of materials that go into renovation and construction also have an impact. According to the U.S. Environmental Protection Agency (EPA), buildings represent 30 percent of the United States' raw material use, and the carbon that is embodied in building materials (via extraction, processing, and manufacturing) is often unnoticed by the public, as it represents a more indirect impact. Recent studies and innovations have been made in the name of operational energy (or the energy that is consumed during the day to day operations within a building); however, less improvement has been observed in investigating and reducing the embodied energy in buildings.

The portion of energy dedicated to embodied energy is becoming a greater portion of a building's overall energy consumption as operational energy consumption continues to decrease due to improvements in energy efficiency. While operational energy still exceeds embodied energy in total, significant savings can potentially be made if more research is dedicated to embodied energy. Churn rate of the building and the lifetimes of the materials must also be taken into consideration when making material choices. Churn rate is the time frame in which a building is renovated or its materials are refreshed. As such, we are focusing our study on the embodied energy contained in typical renovation materials, as well as the effect of various churn rates and the lifetimes of the materials on their overall impact.

This study evaluates typical renovation materials in scenarios constructed from blueprints (from actual buildings in the Los Angeles area), information gleaned from client interviews, and material carbon dioxide and energy impacts collected from various sources to determine which materials have the least impact, and whether the best and worst materials vary once churn rate is considered.

Across building types, wood flooring is observed to have the least impact. Electronics, including computers and televisions played a surprisingly large role in all the total environmental impact of all the scenarios. After electronics, flooring material had the second greatest influence to the total carbon and energy intensities. All the building types were sensitive to the material's lifetime, building churn rates, and material changes. The degree of sensitivity varied amongst the building types depending on the floor plan.

For hotels, it was found that the environmental impact was very sensitive to the frequency of renovations. The recommended length of time to try to keep materials and components in order to reduce impact is 20 years; however, hotels typically need to renovate about every ten to twelve years to stay competitive. Regardless of lifetime, vinyl wall material and wood flooring should be utilized when possible to minimize carbon emissions and energy usage.

For office floors, it was found that the amount each material contributed to the total amount of carbon or energy was sensitive to the frequency of tenant changes. In our simulations, which we call scenarios, tenants were changed out at different rates (churn rate). When the time between tenant changes is 20 years or more, carbon and energy costs are minimized. Another interesting finding is that although carpet plays a very large role in environmental costs, the costs decrease as the time between tenant changes increases. On the contrary, the contribution from computers increases as the time between tenant changes increases.

2. Introduction and Motivation

One of the most pressing environmental issues of our time is that of climate change. Scientists argue that climate change may lead to the greater frequency of extreme weather events such as hurricanes, droughts, heat waves, and flooding. Global temperature has been increasing at an alarming rate, and is projected to continue to increase at a much higher rate than originally predicted. Rise in global temperature has resulted in the melting of ice sheets and glaciers, which has led to sea level rise. As more research is conducted, the connection between climate change and environmental issues such as loss of biodiversity, deforestation, and increased scarcity of freshwater access is becoming stronger. Anthropogenic emissions of carbon dioxide play a huge role in climate change. It is important to understand where and how greenhouse gases are produced, so we can reduce our emissions and our impact on the environment.

An emerging field of study relevant to climate change is life cycle assessment (LCA). LCA is the analysis of the total environmental cost of any material or item. It includes the cost of producing, using, and disposing the product. It is useful for building designers to analyze the life cycle impacts of the materials that go into a building since there may be dozens of renovations during the lifetime of a building. With each renovation of the building comes the replacement of components. The intention of our research is to better understand the environmental cost of specific chosen components of buildings that are typically replaced during these renovations. In regards to the LCA of these components, we focused on the embodied costs. This includes the production of the component, but not the daily use, maintenance, or disposal of the material.

As buildings serve increasing populations, LCA-related changes will transition from being voluntarily pursued benefits to necessities. Providing base materials that can minimize the waste generated during these frequent renovations will help to balance out the high turnover rate that is often observed in these building types. This project will analyze renovations of three building types, and provide recommendations as to how reconstruction and renovation processes can have a lighter carbon footprint.

3. Literature Summary

3.1. Embodied vs. Operational Energy

Energy consumption can be categorized into two types of energy: embodied and operational. Embodied energy represents the energy used to extract, transport, manufacture, process, and maintain all building materials. This energy is related to the structural components of the building rather than energy that is consumed during day-to-day processes within the building, which is termed operational energy.

Advances in technology and the shift of focus of building codes to include energy efficiency requirements in addition to safety requirements have contributed to the improved carbon footprints of buildings; however, these improvements are mainly observed in the operational energy portion of a building's carbon footprint. As more buildings become highly energy-efficient, the portion of a building's carbon footprint that is in need of improvements is now represented by embodied energy. In order to reduce the embodied energy of buildings, it is necessary to compare the various embodied energies of the components that go into the building.

3.2. Lifetime/Churn Rate

The lifetimes of the materials are important to take into consideration when comparing various materials because of the high churn rates of buildings. The average lifetimes of the materials studied are found in Table 1 below. Office and commercial interiors are typically stripped of all components and completely remodeled every time tenants change. It is common for landlords to require tenants to remove all interior finishes and components at the end of their lease period. Hotels also typically experience major remodels every 10 to 12 years because they need to stay contemporary and competitive with newer hotels and competitors. With the short churn rate of the interiors of these building types, it does not make as much sense to choose materials such as marble that last for 75 years if these components will be torn out within 10 to 15 years.

Table 1. Lifetimes of materials.

Flooring Materials	**Lifetime (years)**
Linoleum	30
Wool Carpet	25
Polyamide Carpet	15
Ceramic Tile	50
Marble	75
Wood Floor	45
Wall Materials	
Glass	30
Paint	4
Vinyl	40

Other	
Chair	12.5
Desktops	4
TVs	8
Bathtub	50

3.3. Material Summary

For flooring and wall materials, the functional unit is defined as follows: "The amount of material which is needed to cover one square meter of floor or wall surface". For bulk items/other, the functional unit is defined as one unit of the corresponding item.

3.3.1. Flooring Materials

The flooring materials considered in this study were linoleum, carpet, ceramic tile, marble, and wood flooring.

- *Linoleum*: Linoleum is a flooring material that is made primarily from linseed oil, powdered wood, powdered cork, powdered limestone and pigment. It is generally more durable and has a longer lifetime than other flooring materials such as carpets.
- *Carpets*: There are two main types of carpets: wool carpet and polyamide carpet. Wool carpet is manufactured from wool produced from a 'carpet' sheep, whereas polyamide carpet is produced from polyamide yarn, mainly PA-6 (caprolactam) and PA6.6 (hexamethylenediamine and adipic acid) that originate from crude oil and natural gas (Potting 1996).

- *Ceramic Tile*: Each ceramic tile is assumed to have a density of 28.11 kg per square meter. The raw materials that go into manufacturing ceramic tiles include siliceous sand, feldspars, limestone and some argillaceous materials.(Nicoletti et al. 2002).
- *Marble*: Marble tiles are generally produced from the cutting and polishing of raw marble rocks extracted from quarry sites. For a marble tile with thickness 0.018 meters, the assumed density per marble tile is 48.6 kg per square meter. Marble has one of the longest lifetimes among all materials.
- *Wood flooring*: Wood flooring has the simplest production cycle as the only raw material that goes into the production of wood flooring is wood. The wood is further polished in sawmills and is then transferred to customers for use, with approximately 1 square meter of wood flooring produced per 0.02 cubic meters of wood . Due to its short production cycle, wood flooring is considered to be one of the most environmentally friendly flooring materials.

3.3.2. Wall Materials

The wall materials we studied were paint, vinyl wall coverings, and glass.

- *Paint*: Paint products can be based off of a few substances. The types examined in this study are water, latex, and solvent-based paints. The main raw materials that go into the production of paint are resins, pigments, limestone, and water. It is assumed that every every liter of paint can cover a wall area of 9.789 square meters.
- *Vinyl wall coverings*: Vinyl wall coverings are manufactured from mainly polyvinyl chloride (PVC) that originates from sodium chloride (NaCl), ethylene, crude oil, and electric power (Jonsson et al. 1997). They are often used in hotels because they have much

longer lifetimes than paint and are reportedly more resistant to the wear and tear caused by guests.

- *Glass*: The specific type of glass analyzed for our study is float glass, which is a kind of flat glass produced by a float process that creates glass sheets of uniform thickness with a smooth surface. Float glass generally has a density of 2530 kg per cubic meter, so when assuming a glass wall with a thickness of 0.01 meters, the density becomes 25.3 kg per square meter. Some of the most important raw materials that goes into producing float glass include sand, soda, limestone, dolomite and glass cullet.

3.3.3. Bulk Items/Other

The other items we studied were chairs, toilets, televisions, desktops, and steel/iron for bathtubs.

- *Chairs*: The chairs that we studied are primarily office chairs that serve business, home office, and residential purposes. There are four major raw materials that goes into manufacturing an office chair: plastics, aluminum, steel, and foams/fabrics.
- Televisions (*TVs)*: The three main types of televisions considered in this study are liquid crystal display (LCD) screens, plasma display panel (PDP) screens, and cathode ray tube (CRT) screens. The materials that go into manufacturing a TV are plastics, aluminum, and glass, but can differ depending on the type of screen the TV has.
- *Desktops:* There are two main types of desktop computers for our study: liquid crystal display (LCD) screens and cathode ray tube (CRT) screens. Similar materials that go into manufacturing a television are also used in the production of computers, but can also differ depending on screen type.

- *Steel/Iron (Bathtubs):* As there was no literature or data available on the embodied costs of bathtubs, we approximated the embodied energy of a bathtub by assuming that 1 bathtub consists of 200 kg of cast iron. The production of iron consumes large quantities of energy, and is often one of the most energy consuming industrial sectors (Worrell et al. 2001). Although the embodied energy of the raw materials used in steel/iron production is relatively smaller, the intensive burning of fossil fuels during the manufacturing phase makes up a significant portion of total embodied energy to steel/iron (Price et al. 2002).

4. Goals and Objectives

Our goal was to distinguish the materials and techniques used in interior renovation that result in the minimum embodied carbon and energy costs. We compared a number of different combinations of materials and furnishings in both office spaces and hotels to determine the most optimal material choices, while taking into consideration the lifetimes of the materials as well as the churn rates of the buildings.

The overarching aim was to distinguish the components that make up the greatest proportion of the total embodied carbon or energy so building owners and tenants can focus their attention on these reducing the use of or finding alternatives for these materials to further improve the energy efficiencies of their buildings. From the results, we hoped to suggest the best materials to use for flooring or wall coverings and also give a recommendation for the most optimal length of time to keep materials in use.

5. Methodology

Our method of determining the embodied carbon (CO2) and energy of the materials was by compiling data from literature as well as a material database from a software called Building for Environmental and Economic Sustainability (BEES), created by the National Institute of Standards and Technology. The BEES database includes environmental data for 230 building products. The majority of the literature used were peer-reviewed articles from journals and the rest were manufacturer published environmental reports.

For each material, we gathered information regarding the embodied carbon (kg CO2 per unit) and embodied energy (MJ per unit from one or more sources and computed an average, as well as the minimum and maximum. We compiled this information into a material database on Excel and used this to build our scenarios (See Figure 17 in Appendix A for an example of our material database for chairs).

We based our study on two different building types: commercial office buildings and hotels. We were given the floor plans to a typical four-star hotel in Los Angeles and a few Class A commercial buildings in downtown Los Angeles. We used a program called Bluebeam Vu to measure the area of the flooring, walls, and counted the number of desks, chairs, and computer monitors used in each situation. Based on the floor plans and the materials indicated on the legends of the floor plans, we built realistic "original" scenarios based on actual existing buildings.

After adding up the total embodied carbon and energy of the original scenarios, we did several alternative scenarios. In these alternative scenarios, we switched out components, changed the lifetimes of the materials, or changed the churn rate of the building. Our unit of study for hotels was one entire hotel room and for office buildings was one floor of a typical commercial building. We set up the project this way so it would be easy to see which material choices contribute the most to the overall footprint of each building type, and also so we can give recommendations for the best material choices.

5.1. Literature Search

In order to evaluate these scenarios, data had to be obtained regarding the energy and carbon embodied per unit of each material. This data was obtained from life cycle inventory databases such as the National Institute of Standards and Technology's Building for Environmental and Economic Sustainability (BEES) Online Software and the National Renewable Energy Library (NREL)'s Life Cycle Inventory (LCI) Database. Additional carbon and energy data was gathered from various academic articles. We aimed to collect multiple data points for each renovation component so our analysis would stem from a wider background of studies. Many of our reports came from scientific journals such as the Journal of Cleaner Production, The International Journal of Life Cycle Assessment, Building and Environment, and Energy; among others. Also used were product environmental profiles and purchase orders of materials provided by clients.

5.2. Material database

Material data was input into a master data file on Excel, with specifications such as the material lifetime and the unit of analysis. To keep units constant between sources of each material, some conversions had to be made, such as converting CO2-equivalents per kg of material to CO2-equivalents per square meter of material. For other sources, conversion factors from the EPA's Greenhouse Gas Equivalencies Calculator were used to obtain energy data for materials with only CO2-equivalents given, and vice versa. This material database is referenced to in all of our scenarios, in order to keep results consistent.

5.3. Bluebeam Vu Area and Length Takeoffs

To construct realistic scenarios, we based our dimensions one blueprints of one hotel type and two office building types in Los Angeles. Their specific locations are not disclosed to protect the privacy of the building owners. Using Bluebeam Vu software and PDF files of the blueprints, we were able to collect the length, height, and area take-offs of the hotel rooms and office floors. The PDF files contained a scale that Bluebeam is able to use to calculate the dimensional results of the areas selected. Furniture, computers, and television units were also accounted for in the blueprints. These measurements as well as furniture and technology counts were also input into the master data file in Excel, where they were referenced in the various scenarios.

5.4. Excel LOOKUP Function

To run the scenarios, material impacts and lifetimes, as well as the churn rates of the buildings need to be accounted for. To keep our data consistent, we stored all of our gathered data from the literature search in the Material Master File, then used the Excel LOOKUP function to reference these numbers in the various scenarios. Having one centralized location for our numbers allowed us to make any updates that were necessary with the addition of a new data source, without having to manually change every scenario and risk inconsistent results. Averages and standard deviations for each material type were also calculated and featured using this tool.

To account for lifetime and churn rate, the number of replacements made for a material for a given churn time span was calculated by dividing the churn time span by the material's lifetime and rounding up to the nearest whole number. For example, if we considered a building lifetime of 10 years, then the material paint, which has a lifetime of 4 years, would be replaced 3 times.

5.5. Assumptions

Due to some fundamental limitations, the following assumptions are made in this study:

- Data excerpted from different studies for the same material are assumed to be produced under similar system boundaries.
- All data obtained are related to the material's embodied energy only and does not include operational energy.
- The lifetime assumed for each material is based on the values found in literature and is listed in Table 1.
- For any data point that lacks a carbon or energy value, the missing value is calculated by using a conversion factor: 0.1688 kg CO2/MJ, which is provided by the MIT Energy Club and based on the United States average electricity mix.
- For data points that did not have units measured in square meters, a conversion is made using an assumed density or dimension from BEES. The assumed densities are stated in section 3.3.1 Material Summary.
- Desks and doors, which did not have LCA data available in literature, are assumed to be made entirely of wood with the dimensions D2" x W60" x H36" and W36" x H80", respectively.
- For office scenarios, the embodied energy of the "core of the building" is assumed to stay constant during each renovation. The “core of the building” includes the elevator lobby, stairs, mechanical areas, bathrooms, and electric room.

5.6. Office Scenarios

Two types of offices were studied: a financial services office and a law firm. We based our office study on two floors of actual buildings in downtown Los Angeles. One floor was chosen from each office type and these two floors represent the “original” office scenarios. All other alternative scenarios are adapted from these two floors.

Measurements of the flooring were taken from the floor plans. When measuring the floors, the core of the building was not considered. The core of the building includes the bathroom and floor space adjacent to the elevators and staircases. The types of flooring measured were carpet, marble, linoleum, and vinyl.

The amount of wall area was also measured based on the office’s floor plans. When measuring the walls, the doors were considered part of the wall. The purpose was to measure the amount of paint and glass walls.

Other components of the financial services and law firm floors, such as doors, office chairs, private office desks, cubicle desks, televisions, and monitors were counted. All the measurements for the two floors were used in the original scenario shown in Table 2 below. The lifetimes of the components are also shown in this table. All the lifetimes are based on what was indicated on BEES, with the exception of televisions, desktop monitors, and glass, which were decided on based on other literature sources.

Table 2. Component lifetimes and measurements of original scenarios for the office floors.

Component	Lifetime (years)	Financial Service Floor	Law Firm Floor
Polyamide Carpet Flooring	15	667.799 m2	-
Wool Carpet Flooring	25	11.148 m2	-
Marble Flooring	75	161.79 m2	208.80m2
Linoleum Flooring	30	26.0129 m2	-
Vinyl Flooring	40	62.0087 m2	32.52m2
Ceramic Tile Flooring	50	-	27.23m2
Painted Wall Area	4	963.22 m2	1653.02m2
Glass Wall Area	30	-	176.84m2
Office Chairs	12.5	103	98
Televisions	8	3	4
Computers	4	60	36

In addition to the original scenario, there are 11 alternative scenarios shown in Table 3. One of the parameters of the scenarios is the time frame. This is the length of time that the material will be used. Changing the time frame has an effect on carbon and energy costs because the number of times that the components need to be replaced will depend on the time frame. Besides time frame, another parameter studied was the building components themselves. This was calculated by dividing the components into three groups: flooring, wall materials, and other individual components. The components that are part of each group are as follows.

- Flooring: polyamide carpet flooring, wool carpet flooring, marble flooring, linoleum flooring, vinyl flooring, and ceramic tile flooring.
- Wall material: paint and glass walls
- Individual components: doors, office chairs, private office desks, cubicle desks, televisions, and desktop monitors

Under each of the three component categories, the parameters are defined. The definitions of some terms used are as follows:

- Average: The components for that category were kept the same as the original scenario, but the average carbon and energy data values among all the sources for each material were used.
- Minimum value: The component and literature source with the lowest carbon and energy values for the whole category were used.
- Maximum value: The component and literature source with the highest carbon and energy values for the whole category were used.

Table 3. Ten alternative scenarios.

Scenario	**Flooring Material**	**Wall Material**	**Individual Components**	**Time Frame (yr)**
1	Averages	Averages	Averages	20
2	Maximum value	Maximum value	Maximum value	20
3	Minimum value	Minimum value	Minimum value	20
4	Averages	50% painted walls to glass walls	Averages	20
5	Carpets to wood flooring	Averages	Averages	20
6	Carpet to marble	Averages	Averages	20
7	Averages	Averages	Averages	no specified time period
8	Averages	Averages	Averages	5
9	Averages	Averages	Averages	10
10	Averages	Averages	Averages	50
11	Averages	Averages	Averages	100

5.7. Hotel Scenarios

In evaluating our hotel scenarios, we obtained dimensions from two room types in a typical four-star hotel located in Los Angeles. One room type was a standard 350 square ft room and the second was a larger, 450 square ft room. Dimensions were obtained using blueprint files as described above, and were then incorporated into scenarios with the data gathered in our literature search. A description of each hotel scenario is shown in Table 4 below.

Table 4. Hotel Scenarios

Scenario	Description	Churn Rate
1	Standard hotel room, average values for all material types are used to calculate embodied CO2 and Energy.	--
2	The maximum *carbon average* by material is used in this scenario.	--
3	The most intensive *carbon* data (taken from an individual study, not an average) is input for each material type.	--
4	The maximum *energy average* by material is used in this scenario.	--
5	The most intensive *energy* data (taken from an individual study, not an average) is input for each material type.	--
6	The minimum *carbon average* by material is used in this scenario.	--
7	The least intensive *carbon* data (taken from an individual study, not an average) is input for each material type.	--

8	The minimum *energy average* by material is used in this scenario.	--
9	The least intensive *energy* data (taken from an individual study, not an average) is input for each material type.	--
10	Changing carpet and tile to marble flooring in bedroom and bathroom.	--
11	Installation of UPC Carpet in the bedroom.	--
12	The full glass wall bordering the balcony is switched to a wall framing a large sliding glass door.	--
13	Installation of wooden floors in the bedroom.	--
14	Switching from one combined shower and bathtub unit to a separate bath and shower.	--
15	Solvent paint is used as the main wall covering.	--
16	Average Values for Paint are used to represent the main wall covering.	--
17	Materials are changed every 5 years over a 50 year lifetime	5 years
18	Materials are changed every 10 years over a 50 year lifetime	10 years
19	Materials are changed every 20 years over a 50 year lifetime	20 years

6. Results

6.1. Materials

6.1.1. Flooring Materials

The average carbon intensity for linoleum was 5.234 kg/m^2 and the average energy intensity was 157.205 MJ/m^2. When taking lifetime into consideration, the average carbon and energy intensities for linoleum become 13.603 kg/m^2 and 604.072 MJ/m^2, respectively. The average carbon intensity for carpet was 66.913 kg/m^2 and the average energy intensity was 559.119 MJ/m^2. When taking lifetime into consideration, the average carbon and energy intensities for carpet become 267.656 kg/m^2 and 2236.476 MJ/m^2, respectively. The average carbon intensity for ceramic tile was 23.58 kg/m^2 and the average energy intensity was 192.899 MJ/m^2. When taking lifetime into consideration, the average carbon and energy intensities for ceramic tile become 42.569 kg/m^2 and 344.211 MJ/m^2, respectively. The average carbon intensity for marble was 34.613 kg/m^2 and the average energy intensity was 564.66 MJ/m^2. When taking lifetime into consideration, the average carbon and energy intensities for marble are still 34.611 kg/m^2 and 564.66 MJ/m^2, respectively. This is because marble has the longest lifetime among all the flooring materials of 75 years, so the other materials were normalized to a lifetime of 75 years. The average carbon intensity for wood flooring was 0.496 kg/m^2 and the average energy intensity was 2.935 MJ/m^2. When taking lifetime into consideration, the average carbon and energy intensities for wood flooring become 0.991 kg/m^2 and 5.871 MJ/m^2, respectively.

See Figure 1 below for the average carbon and energy intensities of the five flooring materials and see Figure 2 below for the average carbon and energy intensities of the flooring materials when taking lifetime into consideration. The error bars in Figures 1 and 2 show the minimum and maximum data points of each material. All of the above carbon and energy data is also found in Table 5 below.

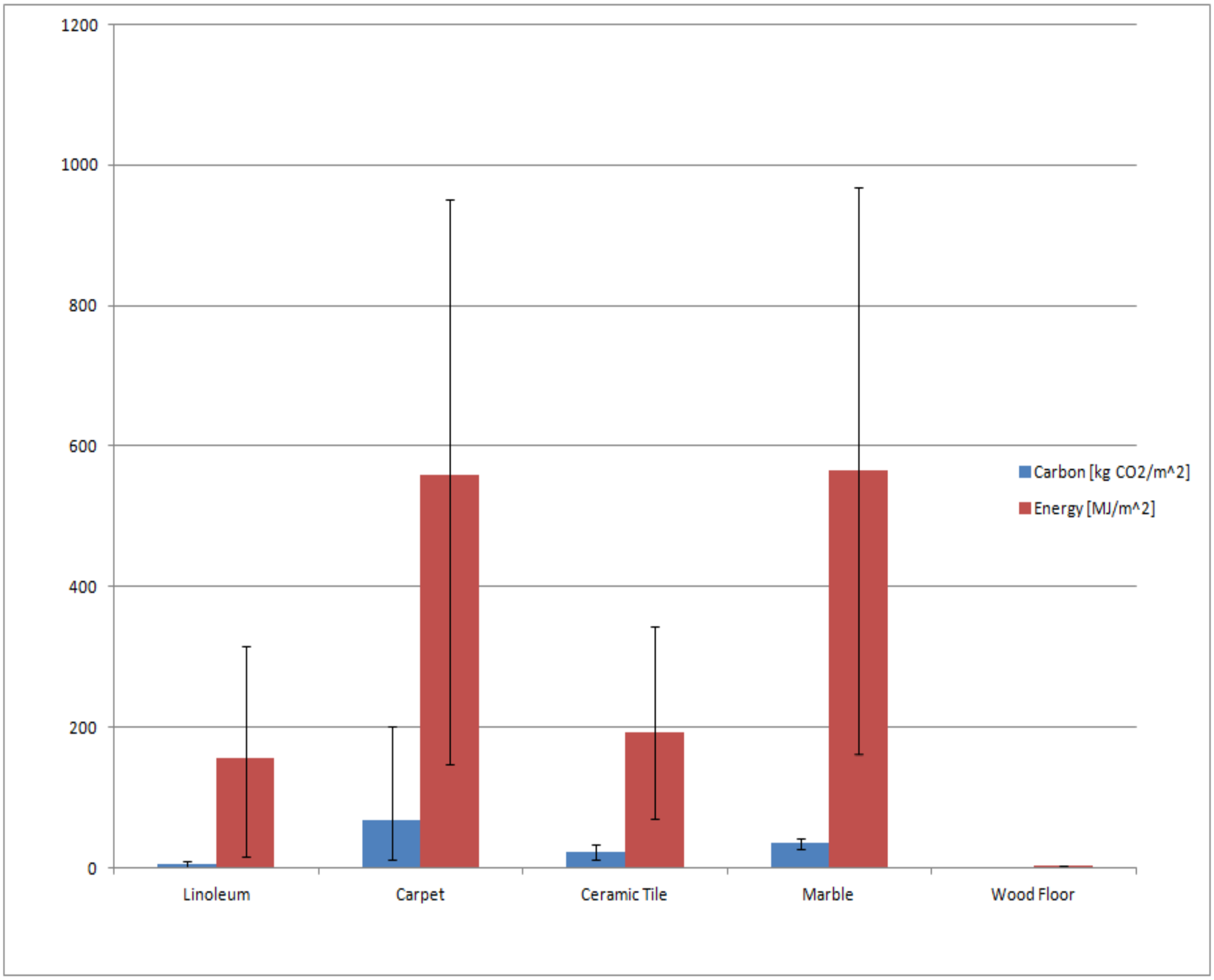


Figure 1. Average carbon and energy intensities of flooring materials.

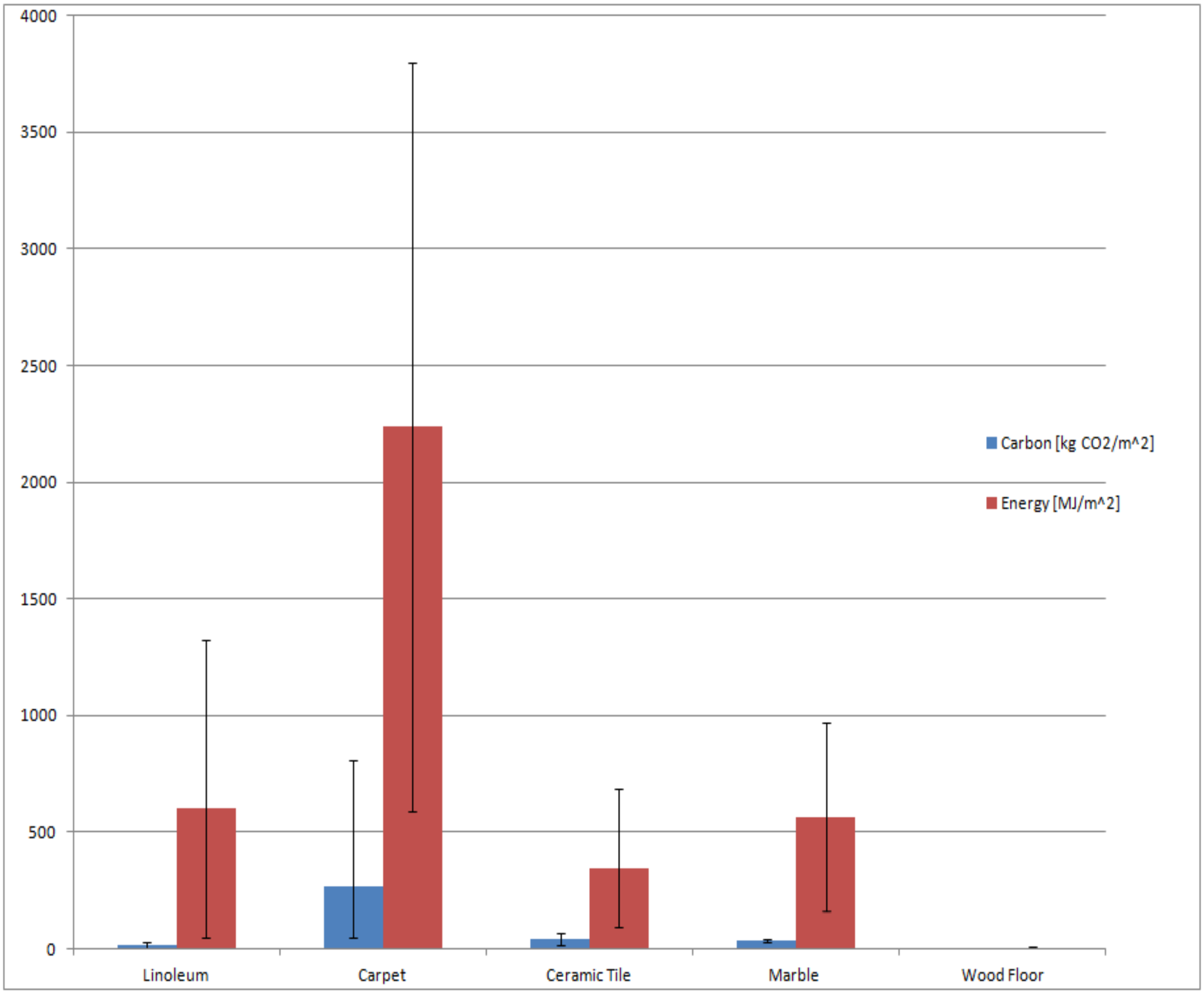


Figure 2. Average carbon and energy intensities of flooring materials (lifetimes considered).

6.1.2. Wall Materials

The average carbon intensity for glass was 49.495 kg/m^2 and the average energy intensity was 406.825 MJ/m^2. When taking lifetime into consideration, the average carbon and energy intensities for glass become 98.99 kg/m^2 and 813.65 MJ/m^2, respectively. The average carbon intensity for paint was 0.383 kg/m^2 and the average energy intensity was 2.894 MJ/m^2. When taking lifetime into consideration, the average carbon and energy intensities for paint become 3.832 kg/m^2 and 28.942 MJ/m^2, respectively. The average carbon intensity for vinyl was 7.168 kg/m^2 and the average energy intensity was 83.763 MJ/m^2. When taking lifetime into consideration, the average carbon and energy intensities for vinyl are still 7.168 kg/m^2 and 83.763 MJ/m^2, respectively. This is because vinyl has the longest lifetime among all the wall materials of 40 years, so the other materials were normalized to a lifetime of 40 years.

See Figure 3 below for the average carbon and energy intensities of the three flooring materials and see Figure 4 below for the average carbon and energy intensities of the wall materials when taking lifetime into consideration. The error bars in Figures 3 and 4 show the minimum and maximum data points of each material. All of the above carbon and energy data is also found in Table 5 below.

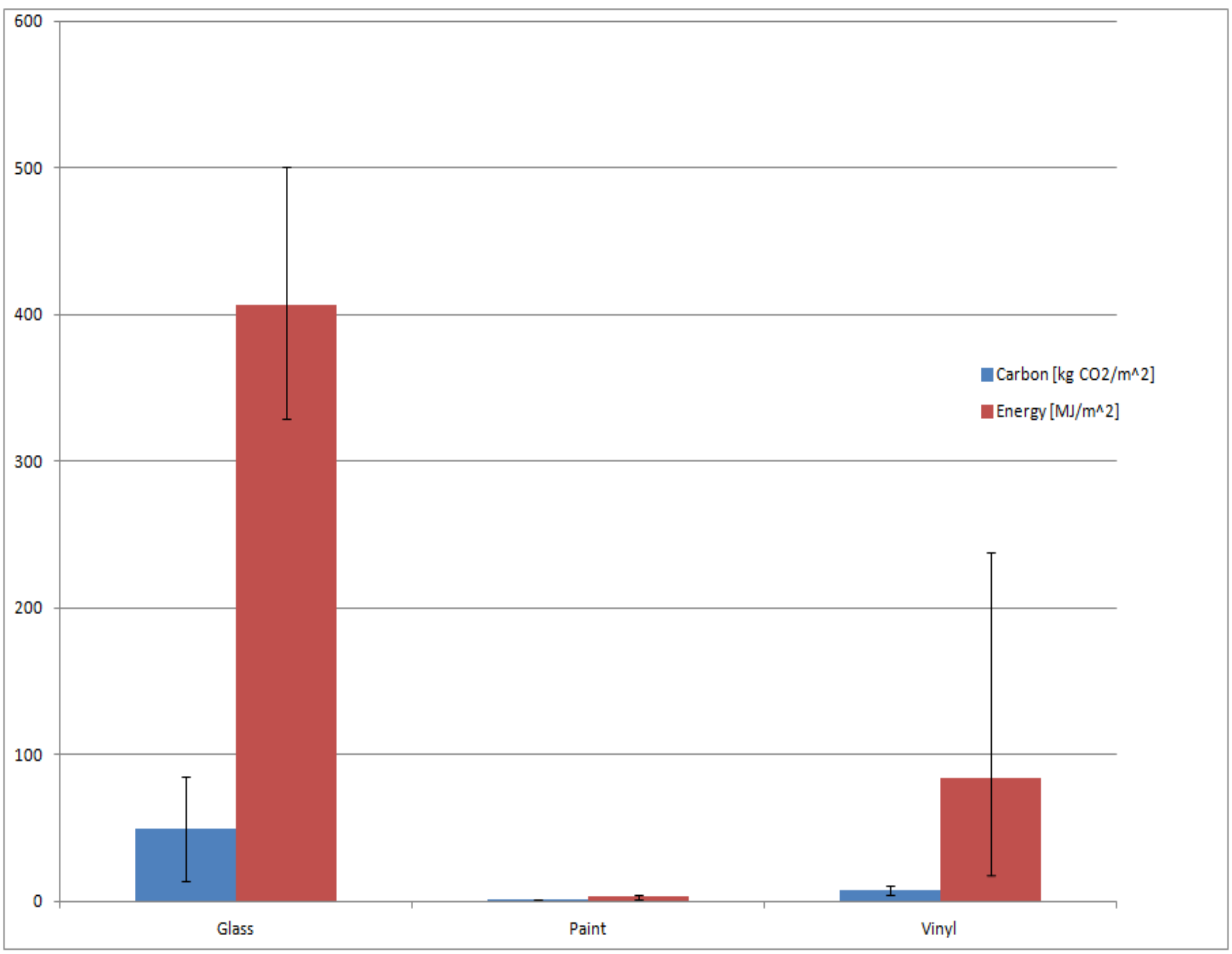


Figure 3. Average carbon and energy intensities of wall materials.

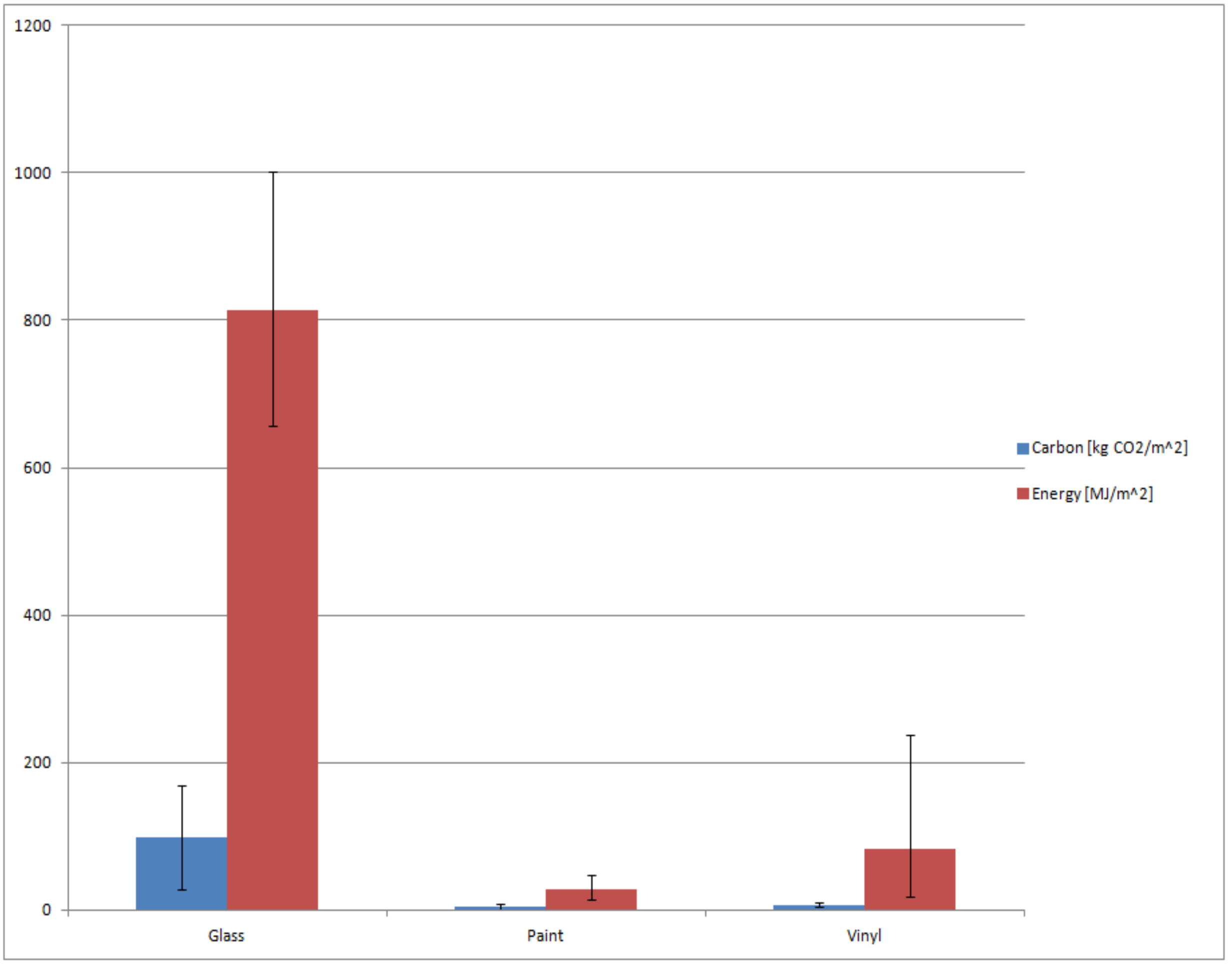


Figure 4. Average carbon and energy intensities of wall materials (lifetimes considered).

6.1.3. Bulk Items/Other

The average carbon intensity for chairs was 192.244 kg/chair and the average energy intensity was 2541.732 MJ/chair. When taking lifetime into consideration, the average carbon and energy intensities for chairs become 769.01 kg/chair and 10166.933 MJ/chair, respectively. The average carbon intensity for desktops was 771.533 kg/desktop and the average energy intensity was 946.918 MJ/desktop. When taking lifetime into consideration, the average carbon and energy intensities for desktops become 5400.733 kg/desktop and 6628.428 MJ/desktop, respectively. The average carbon intensity for TVs was 395.76 kg/TV and the average energy intensity was 1687.572 MJ/TV. When taking lifetime into consideration, the average carbon and energy intensities for TVs become 2770.32 kg/TV and 11813.004 MJ/TV, respectively. The average carbon intensity for bathtubs was 1056.6 kg/bathtub and the average energy intensity was 6260 MJ/bathtub. When taking lifetime into consideration, the average carbon and energy intensities for bathtubs is still 1056.6 kg/bathtub and 6260 MJ/bathtub, respectively. This is because bathtubs had the longest lifetime among the bulk items of 50 years, so the other items were normalized to 50 years. See Figure 5 for the average carbon and energy intensities of the three flooring materials and see Figure 6 for the average carbon and energy intensities of the wall materials when taking lifetime into consideration. The error bars in Figures 5 and 6 show the minimum and maximum data points of each material. All of the above carbon and energy data is also found in Table 5 below.

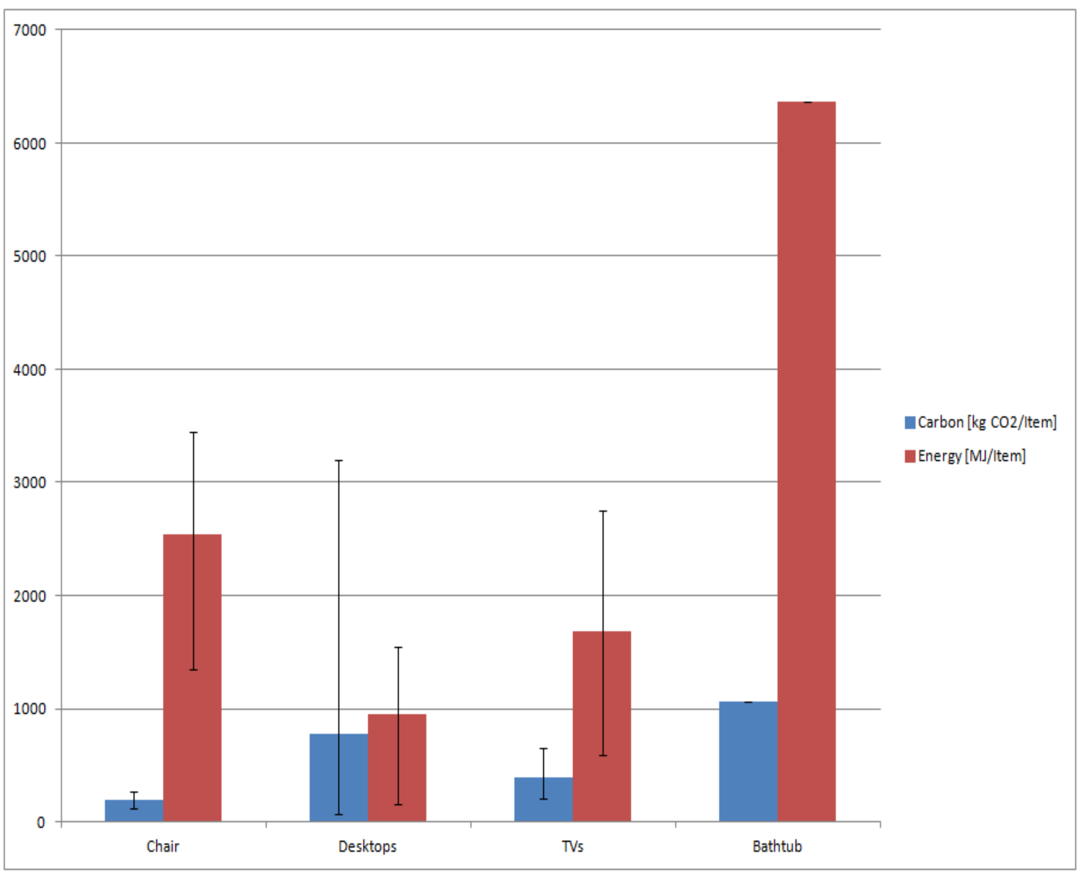


Figure 5. Average carbon and energy intensities of bulk items.

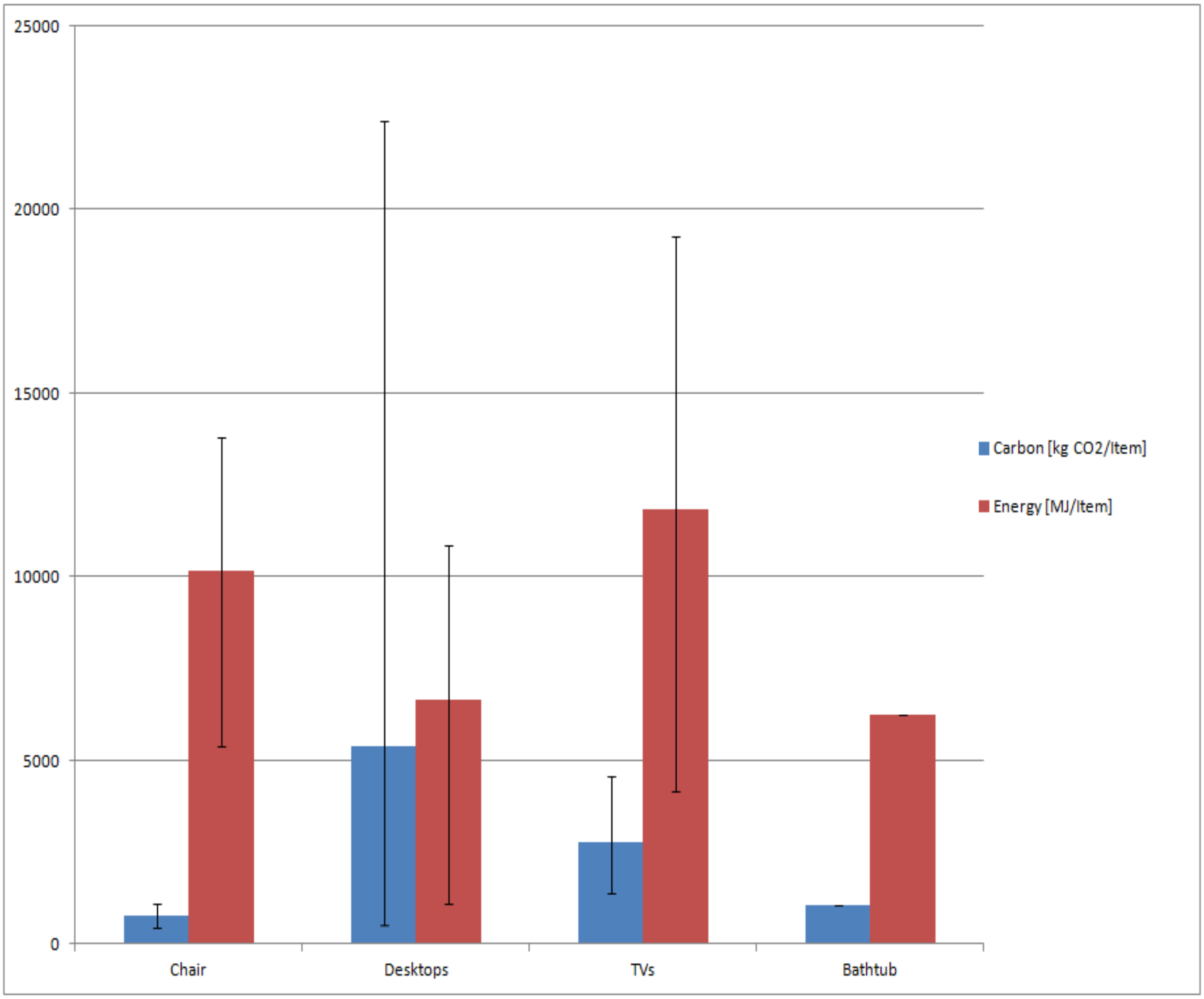


Figure 6. Average carbon and energy intensities of bulk items (lifetimes considered).

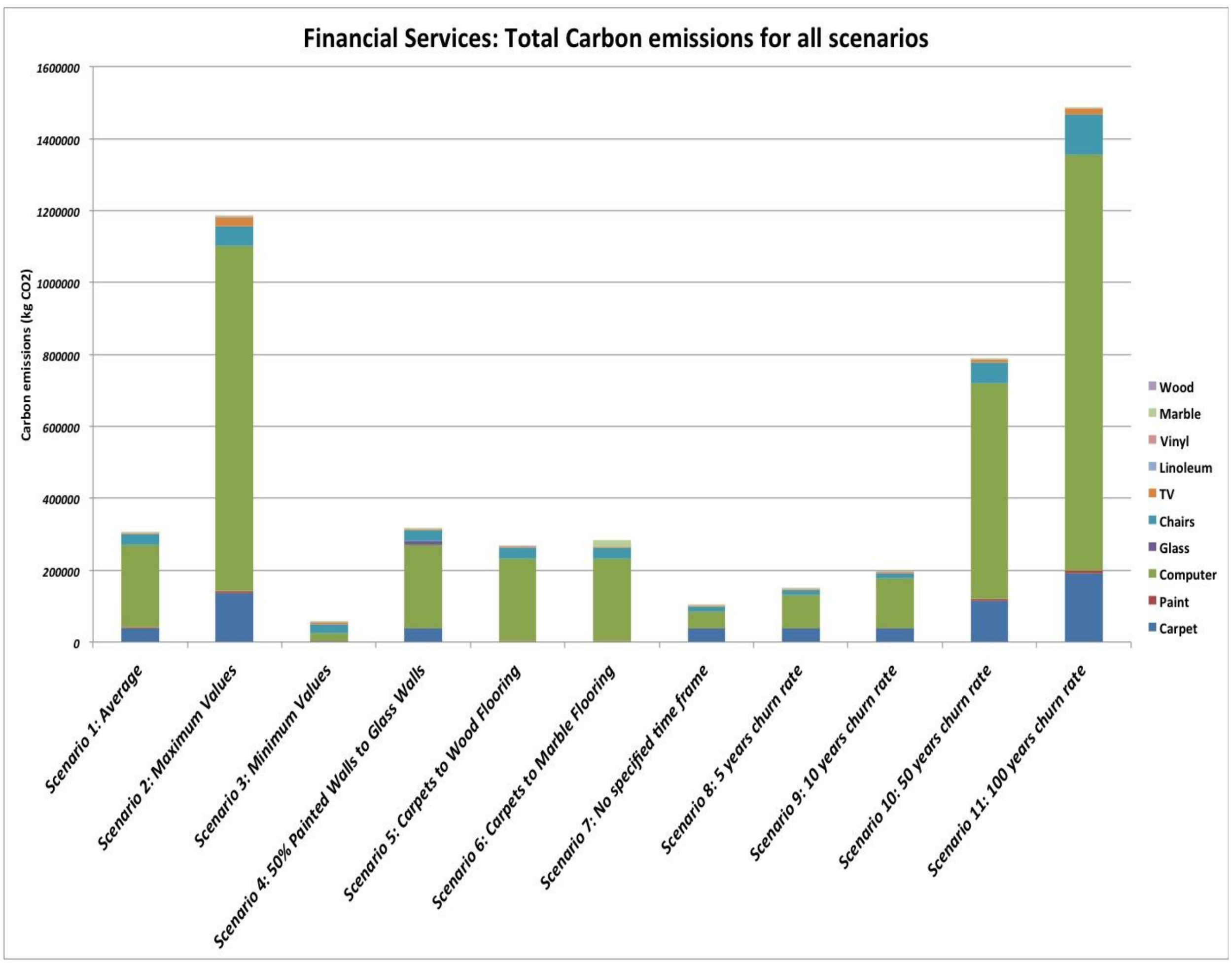
Table 5. Average carbon and energy intensities of all materials.

	Average Carbon (kg/m^2)	**Average Carbon - Lifetimes Considered** (kg/m^2)	**Average Energy** (MJ/m^2)	**Average Energy - Lifetimes Considered** (MJ/m^2)
Flooring Materials				
Linoleum	5.234	13.603	157.205	604.072
Carpet	66.913	267.656	559.119	2236.476
Ceramic Tile	23.58	42.569	192.899	344.211
Marble	34.613	34.611	564.66	564.66
Wood Floor	0.496	0.991	2.935	5.871
Wall Materials				
Glass	49.495	98.99	406.825	813.65
Paint	0.383	3.832	2.894	28.942
Vinyl	7.168	7.168	83.763	83.763

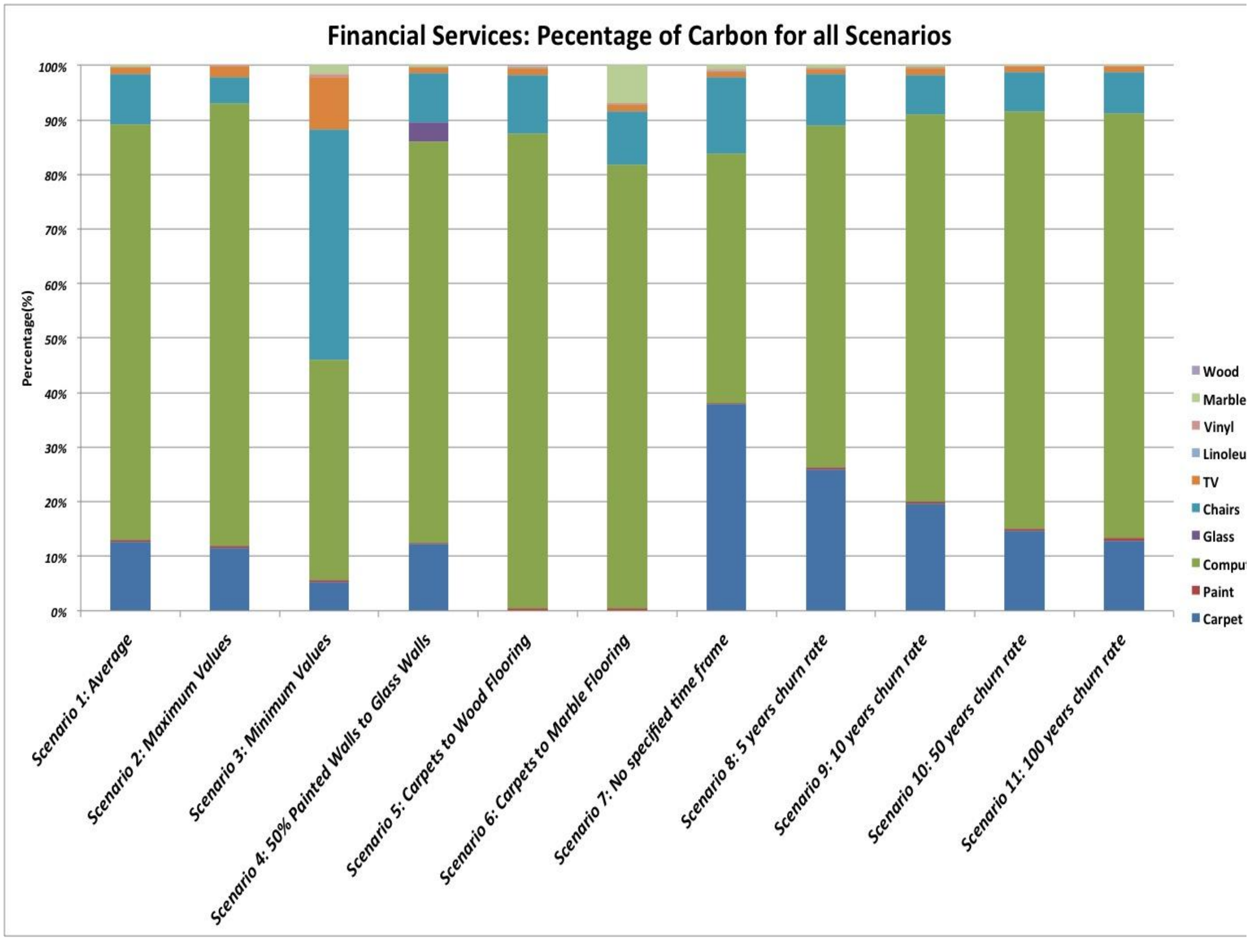
Other				
Chair	192.244	769.01	2541.732	10166.933
Desktops	771.533	5400.733	946.918	6628.428
TVs	395.76	2770.32	1687.572	11813.004
Bathtub	1056.6	1056.6	6260	6260

6.2. Office Scenarios

7 (A)

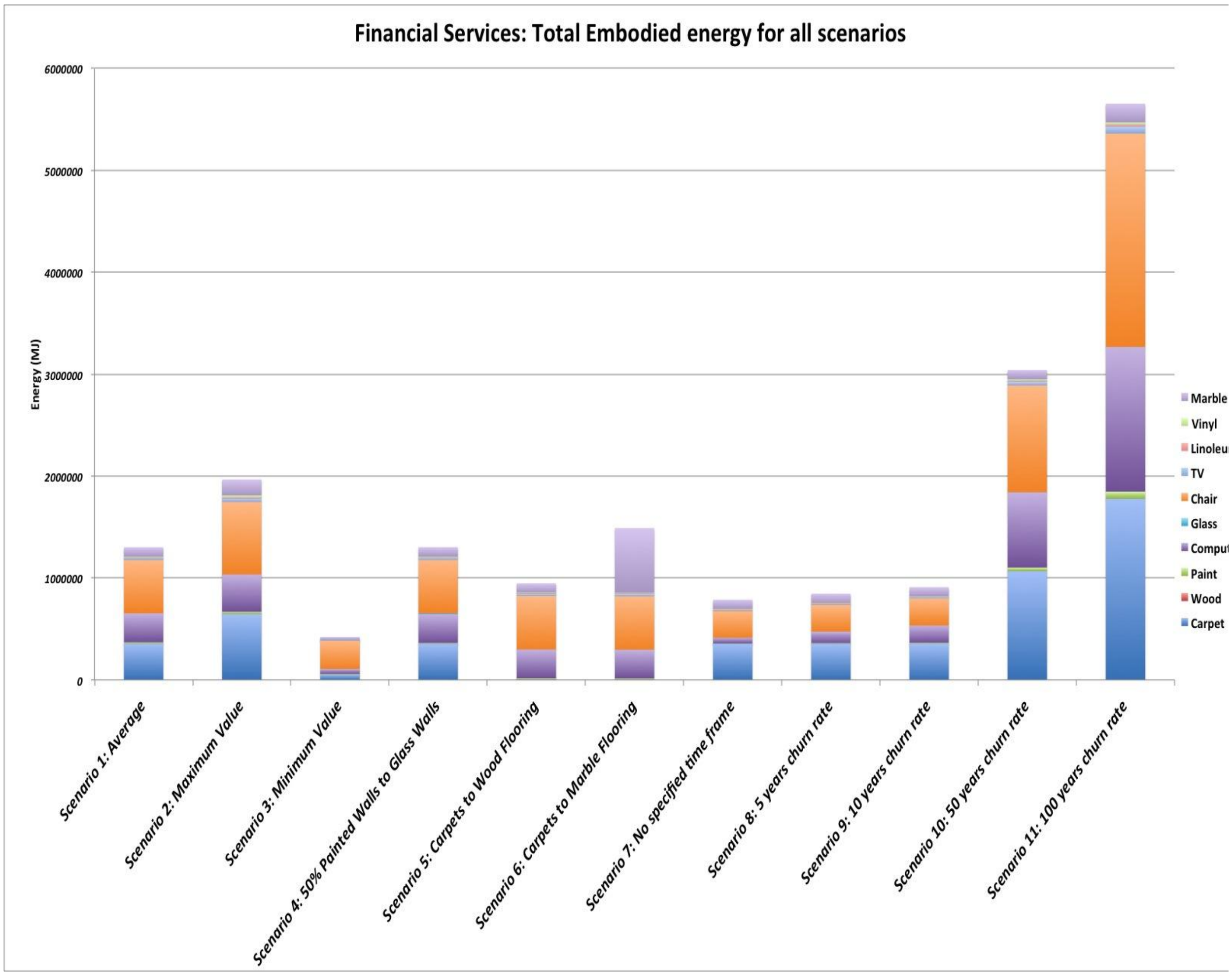


7 (B)

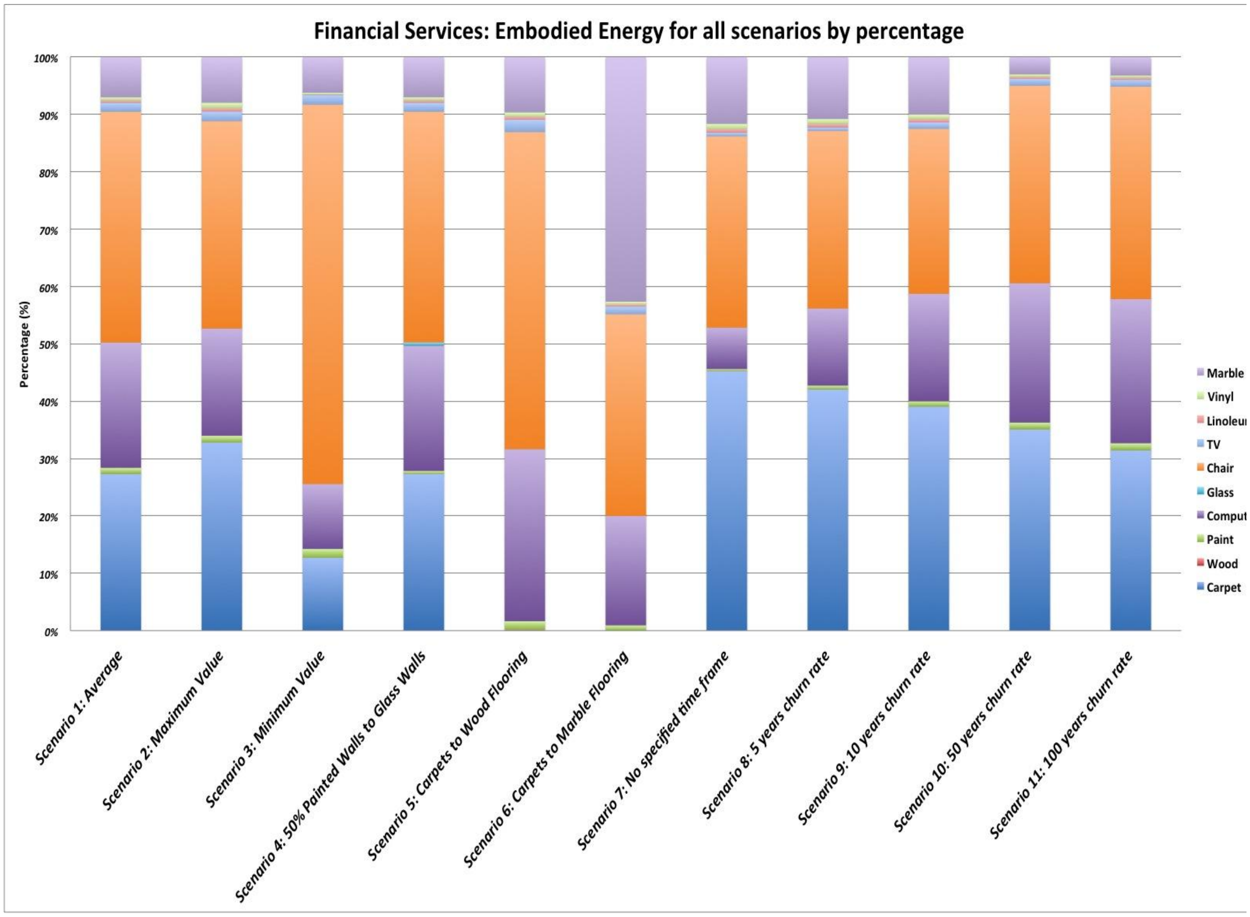


Financial Services: Pecentage of Carbon for all Scenarios
Percentage(%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Wood
Marble
Vinyl
Linoleu
TV
Chairs
Glass
Compu
Paint
Carpet
Scenario 1: Average
Scenario 2: Maximum Values
Scenario 3: Minimum Values
Scenario 4: 50% Painted Walls to Glass Walls
Scenario 5: Carpets to Wood Flooring
Scenario 6: Carpets to Marble Flooring
Scenario 7: No specified time frame
Scenario 8: 5 years churn rate
Scenario 9: 10 years churn rate
Scenario 10: 50 years churn rate
Scenario 11: 100 years churn rate

7 (C)

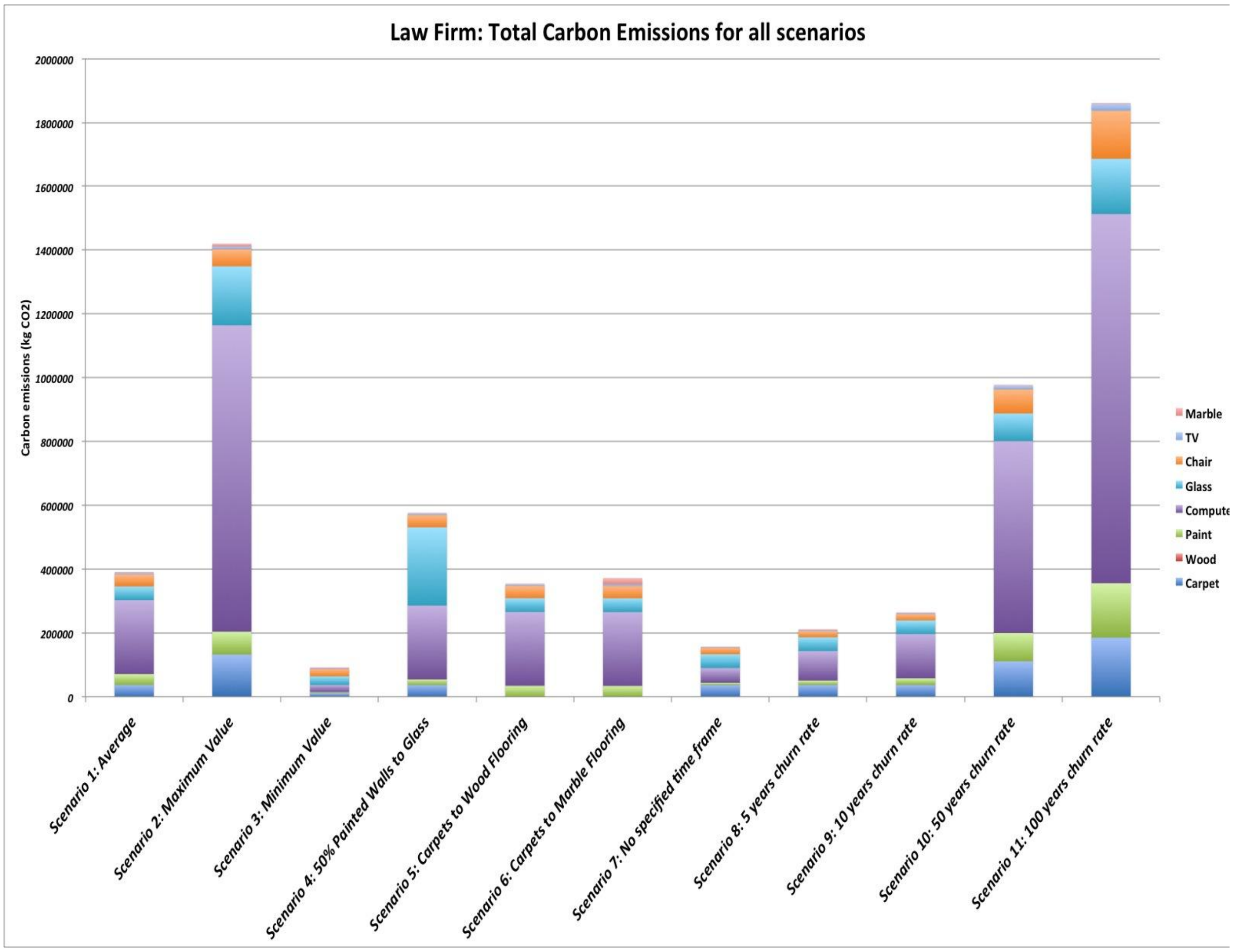

Financial Services: Total Embodied energy for all scenarios
Energy (MJ)
6000000
5000000
4000000
3000000
2000000
1000000
0
Scenario 1: Average
Scenario 2: Maximum Value
Scenario 3: Minimum Value
Scenario 4: 50% Painted Walls to Glass Walls
Scenario 5: Carpets to Wood Flooring
Scenario 6: Carpets to Marble Flooring
Scenario 7: No specified time frame
Scenario 8: 5 years churn rate
Scenario 9: 10 years churn rate
Scenario 10: 50 years churn rate
Scenario 11: 100 years churn rate
Marble
Vinyl
Linoleu
TV
Chair
Glass
Comput
Paint
Wood
Carpet

7 (D)



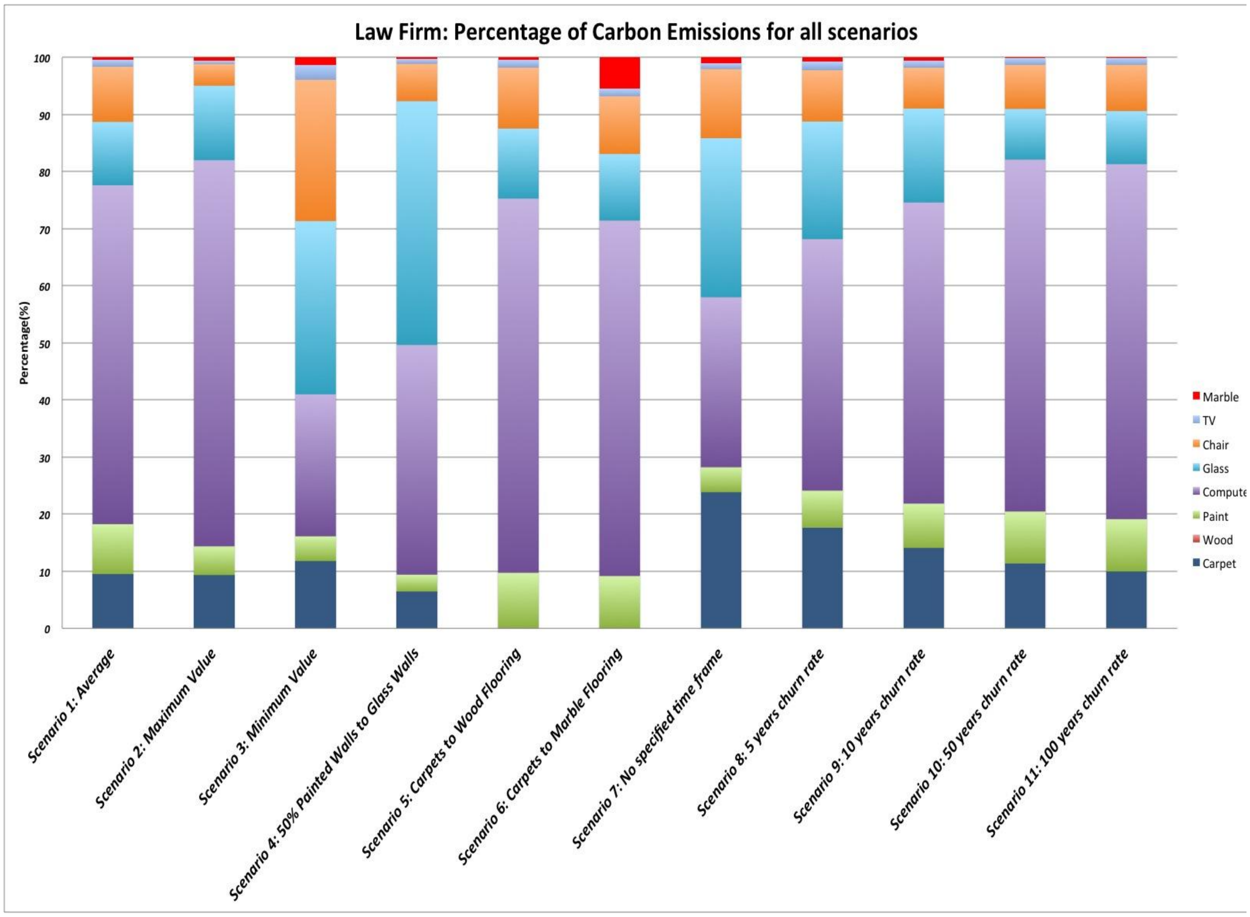
Financial Services: Embodied Energy for all scenarios by percentage
Percentage (%)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Scenario 1: Average
Scenario 2: Maximum Value
Scenario 3: Minimum Value
Scenario 4: 50% Painted Walls to Glass Walls
Scenario 5: Carpets to Wood Flooring
Scenario 6: Carpets to Marble Flooring
Scenario 7: No specified time frame
Scenario 8: 5 years churn rate
Scenario 9: 10 years churn rate
Scenario 10: 50 years churn rate
Scenario 11: 100 years churn rate
Marble
Vinyl
Linoleu
TV
Chair
Glass
Comput
Paint
Wood
Carpet

7 (E)



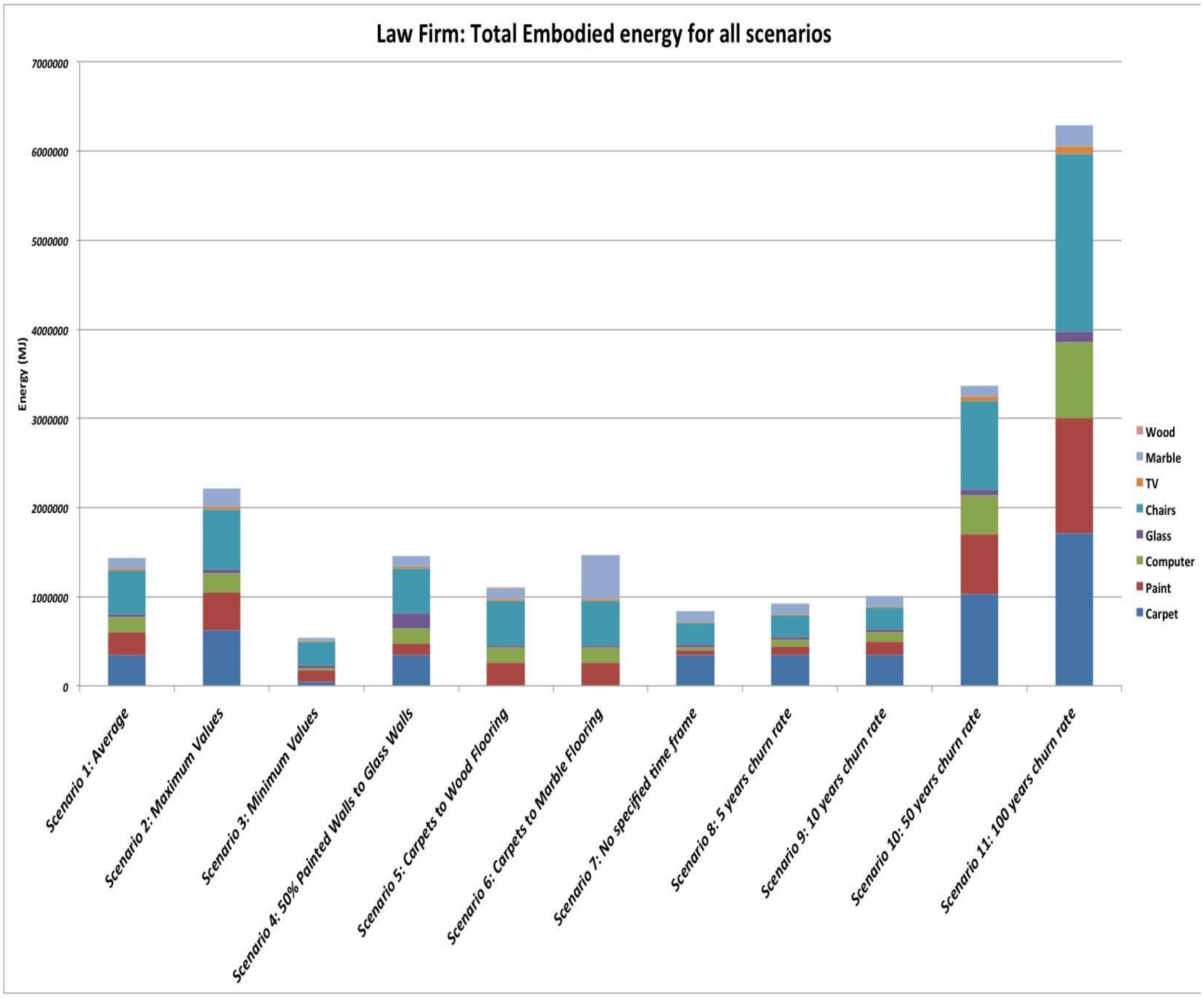
Law Firm: Total Carbon Emissions for all scenarios
Carbon emissions (kg CO2)
2000000
1800000
1600000
1400000
1200000
1000000
800000
600000
400000
200000
0
Scenario 1: Average
Scenario 2: Maximum Value
Scenario 3: Minimum Value
Scenario 4: 50% Painted Walls to Glass
Scenario 5: Carpets to Wood Flooring
Scenario 6: Carpets to Marble Flooring
Scenario 7: No specified time frame
Scenario 8: 5 years churn rate
Scenario 9: 10 years churn rate
Scenario 10: 50 years churn rate
Scenario 11: 100 years churn rate
Marble
TV
Chair
Glass
Compute
Paint
Wood
Carpet

7 (F)



Law Firm: Percentage of Carbon Emissions for all scenarios
Percentage(%)
100
90
80
70
60
50
40
30
20
10
0
Marble
TV
Chair
Glass
Compute
Paint
Wood
Carpet
Scenario 1: Average
Scenario 2: Maximum Value
Scenario 3: Minimum Value
Scenario 4: 50% Painted Walls to Glass Walls
Scenario 5: Carpets to Wood Flooring
Scenario 6: Carpets to Marble Flooring
Scenario 7: No specified time frame
Scenario 8: 5 years churn rate
Scenario 9: 10 years churn rate
Scenario 10: 50 years churn rate
Scenario 11: 100 years churn rate

7 (G)


Law Firm: Total Embodied energy for all scenarios
Energy (MJ)
7000000
6000000
5000000
4000000
3000000
2000000
1000000
0
Wood
Marble
TV
Chairs
Glass
Computer
Paint
Carpet
Scenario 1: Average
Scenario 2: Maximum Values
Scenario 3: Minimum Values
Scenario 4: 50% Painted Walls to Glass Walls
Scenario 5: Carpets to Wood Flooring
Scenario 6: Carpets to Marble Flooring
Scenario 7: No specified time frame
Scenario 8: 5 years churn rate
Scenario 9: 10 years churn rate
Scenario 10: 50 years churn rate
Scenario 11: 100 years churn rate

7 (H)

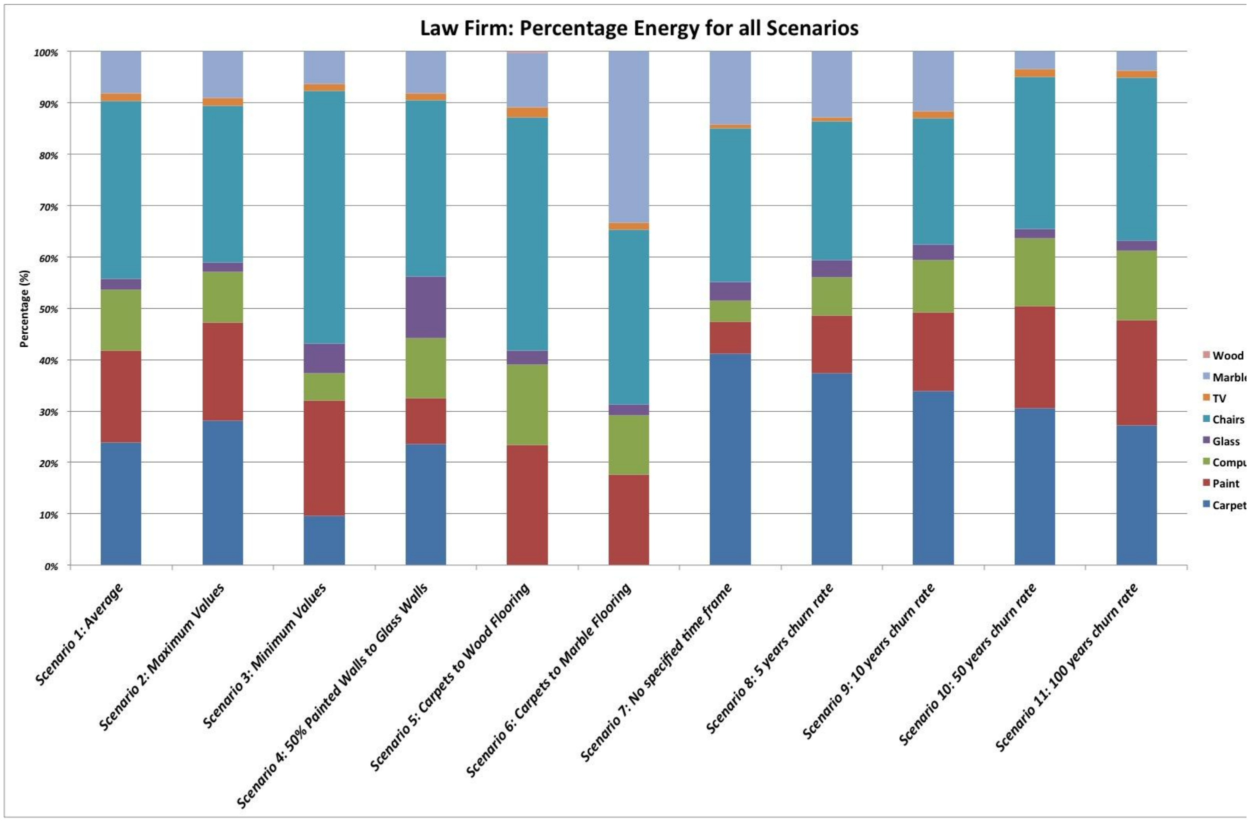


Figure 7. Charts (A) through (H) show the results for all the office scenarios side by side. Charts (A) through (D) are for the financial floor. Charts (E) through (H) are for the law firm floor. All of these scenarios are also shown in pie chart format in Figures 18-21 of Appendix B.

6.2.1. Scenario 1 and 7: Original Floor Plan

Scenario 7 describes the CO2 and energy costs of the components being replaced based on the original floor plan without considering churn rate. The most costly in regards to CO2 are computers and carpet for the financial office, and computers, carpet, and glass for the law firm. The most costly component in regards to energy are carpet and chairs for both floors.

Like scenario 7, scenario 1 describes the CO2 and energy costs of all components being replaced based on the original floor plan. The difference is that there is a churn rate of 20 years and the components are changed during this churn rate based on the lifetime of the material. In this scenario, computers overwhelmingly contributed the greatest to total CO_2 for both floors. All other components contributed less than 15% of the total CO_2 for both floors. On the other hand, the contribution was more evenly distributed for energy. Chairs contributed the most energy for both floors, but other components had large contributions too. For the law firm, carpet contributes 23.86% and paint contributes 17.91%. For the financial office, carpet contributes 27.32% and computers contribute 21.83%.

6.2.2. Scenarios 1-3: Average, Maximum, and Minimum

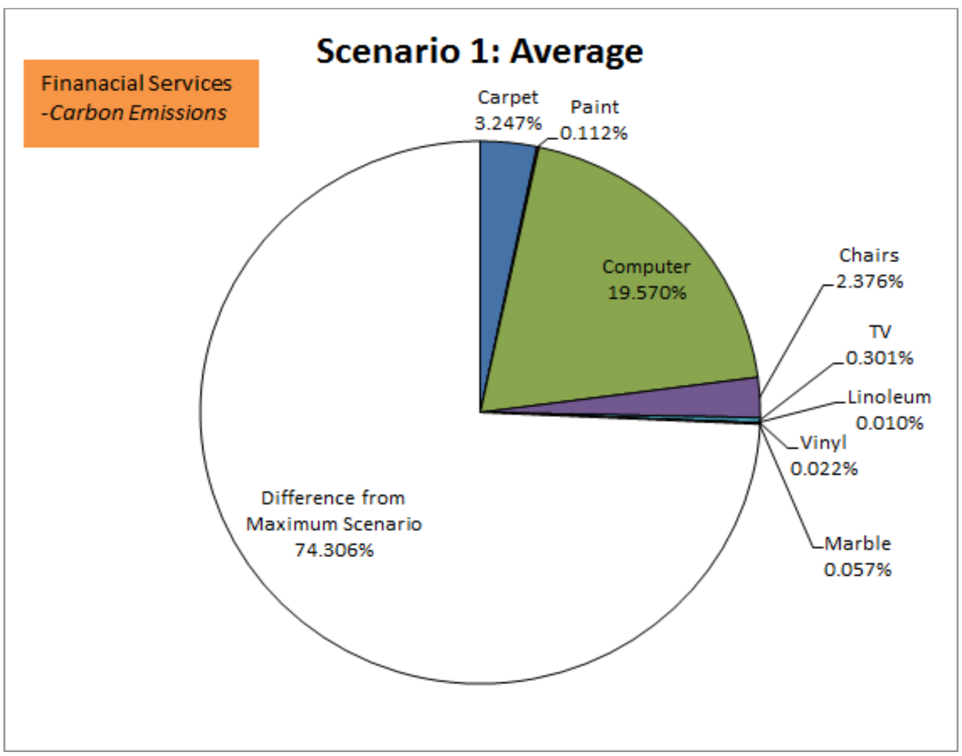
Regardless of floor type, the maximum and minimum scenarios were greatly different in total amount of cost. For the law firm floor, the CO_2 maximum scenario was 15.73 times the minimum scenario and the energy maximum scenario was 4.13 times the minimum energy scenario. For the financial floor, the CO_2 maximum scenario was 21.27 times larger than the minimum scenario and the energy maximum scenario was 4.68 times larger than the minimum scenario. The average differed in that it was closer to the maximum in energy for both floors, but it was closer to the minimum of CO_2 for both floors. This can be seen by difference in CO_2 and energy between scenario 1 (average) and scenario 2 (maximum), shown in Figures 17A and 17B in Appendix B.

Comparing scenario 1 (average) to scenario 3 (minimum) for both floors, chairs increased the greatest and carpet decreased the greatest in percentage of energy from scenario 1 to 3. On the contrary, scenario 2 (maximum) was quite similar to the scenario 1 (average) in regards to the percentage of contribution by component for energy for both floors. For the financial floor, chairs increased from 40.24% to 66.14% contribution and carpet declined from 27.32% contribution to 12.71% contribution. For the law firm floor, chairs increased from 34.64% to 49.30% contribution and carpet declined from 23.86% to 9.61% contribution.

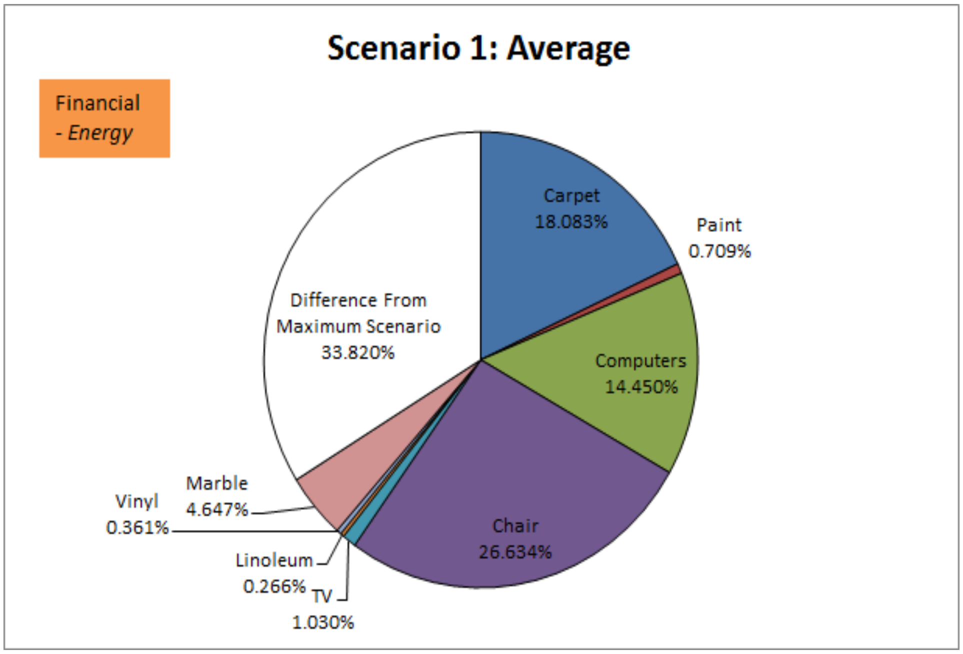
A different trend was seen for CO2 comparing the scenario 1 (average) to scenario 3 (minimum). For the financial floor, chairs increased from 9.25% to 42.23% contribution and computer decreased from 76.16% to 40.35% contribution from scenario 1 (average) to scenario 3 (minimum). For the law firm, chairs increased from 9.66% to 24.75% contribution and computer decreased from 59.36% to 24.86% contribution from scenario 1 (average) to scenario 3 (minimum).

On the contrary to the comparisons between scenario 1 (average) and scenario 3 (minimum), scenario 1 (average) was quite similar to the scenario 2 (maximum) in regards to the percentage of contribution by component for CO2 for both floors.

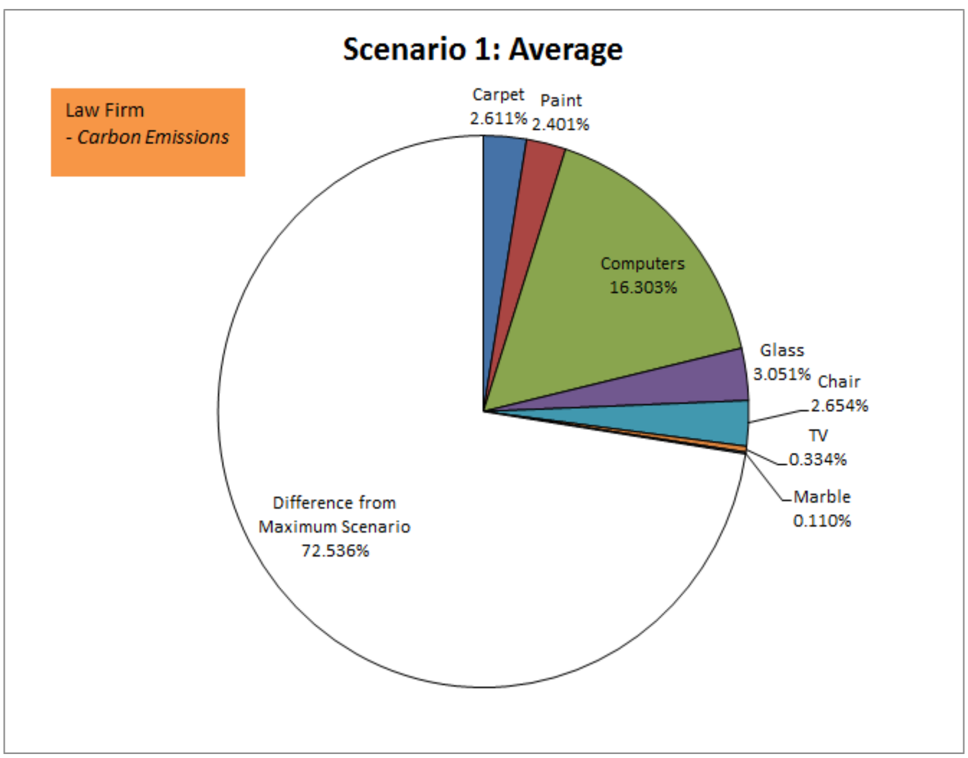
8 (A)



8 (B)


Scenario 1: Average
Financial
- Energy
Carpet
18.083%
Paint
0.709%
Computers
14.450%
Chair
26.634%
TV
1.030%
Linoleum
0.266%
Vinyl
0.361%
Marble
4.647%
Difference From Maximum Scenario
33.820%

8 (C)


Scenario 1: Average
Law Firm
- Carbon Emissions
Carpet
2.611%
Paint
2.401%
Computers
16.303%
Glass
3.051%
Chair
2.654%
TV
0.334%
Marble
0.110%
Difference from Maximum Scenario
72.536%

8 (D)

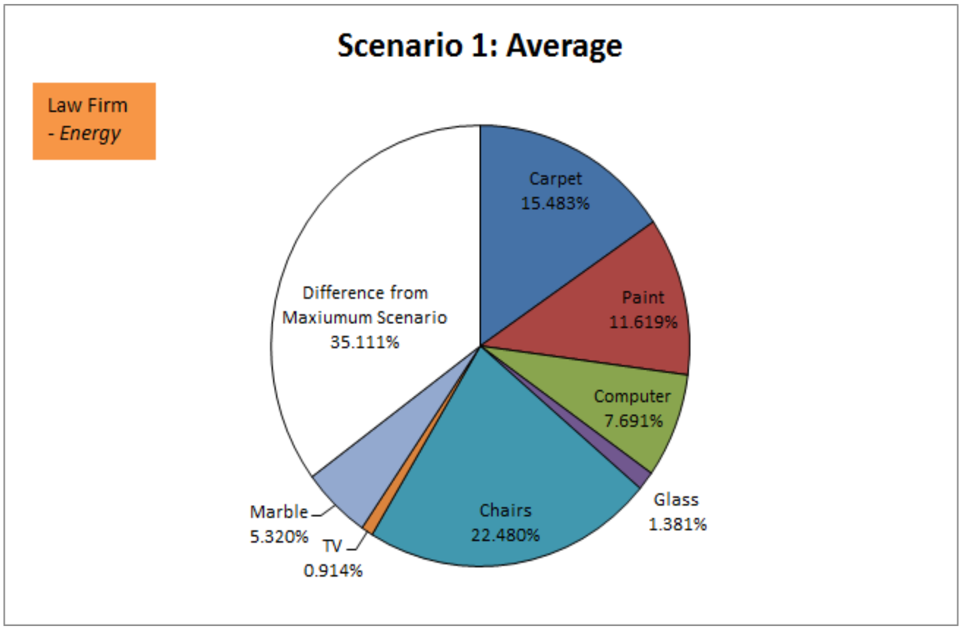


Figure 8. These pie charts show the difference between scenario 2 (maximum) and scenario 1 (average) shown in white. The rest of the colors represent the contribution from each component for scenario 1 (average). (A) is a comparison of financial CO2 scenarios. (B) is a comparison of financial energy scenarios. (C) is a comparison of law firm CO2 scenarios. (D) is a comparison of law firm energy scenarios.

6.2.3. Scenarios 4-6: Changing Materials

Most of the significant difference for material changes came in the form of energy, and only one scenario was significantly different for CO2. The greatest savings came changing carpet to wood flooring. The savings were not as much for CO2, but were significant for energy. For the financial floor, energy dropped from 1,301,039.12 MJ to 947,186.586 MJ from scenario 1 (carpet) to scenario 5 (wood floors). This amounts to a 27.20% decrease in total energy. For the law firm floor energy dropped from 1,437,995.78 MJ to 1,096,756.81 MJ from scenario 1 (carpet) to scenario 5 (wood floors). This amounts to a 23.73% decrease in total energy.

Two scenarios did show a significant increase in CO2 and Energy. First, the law firm floor had a significant increase in CO2 in scenario 4 when 50% of the painted walls were changed to glass walls. CO2 increased from 389,922.938 kg CO2 to 575,326.32 kg CO2 from scenario 1 (original) to scenario 4 (more glass). This amounts to a 47.55% increase in total CO2. Second, both floors had a significant increase in energy in scenario 6 where carpet was changed to marble. For the law firm, the percentage contribution of energy from marble increased greatly. It increased from 8.20% to 33.31% from scenario 1 (carpet) to scenario 6 (marble). However, the total amount of energy overall did not change much between the two scenarios.

For the financial office, both the percent energy contribution from marble and the total energy for the entire scenario increased significantly from scenario 1 (carpet) to scenario 6 (marble). The percent energy contribution from marble increases from 7.02% to 42.65% from scenario 1 (carpet) to scenario 6 (marble). The total for the entire scenario increased from 1,301,039.12 MJ to 1,489,439.41 MJ from scenario 1 (carpet) to scenario 6 (marble). This amounts to a 14.48% increase.

6.2.4. Scenarios 1, 8-11: Changing Churn Rates and Tenant Lifetimes

In regards to the churn rate scenarios, as churn rate decreased (the period of time between tenant changes increases), the total amount of both CO2 and energy over the course of the entire 100 year projection decreased. We found that this total amount of CO2 and energy over 100 years begins to level off at a churn rate of 20 years. These findings are true for both floor types. An example of this trend for the total CO2 of a law firm floor is shown in Figure 9 below. The rest are shown in Figures 22A through 22C in Appendix B.

For both floors and both carbon and energy, the percent contribution of the scenario decreases the greatest for carpet as the lifetime of the tenant increases. On the contrary, the percent contribution increases the greatest for computers in for both floor types. The financial CO2 and energy and the law firm CO2 exhibited this increase in computer contributions. For law firm energy, the greatest increase by percentage is in paint, not computers.

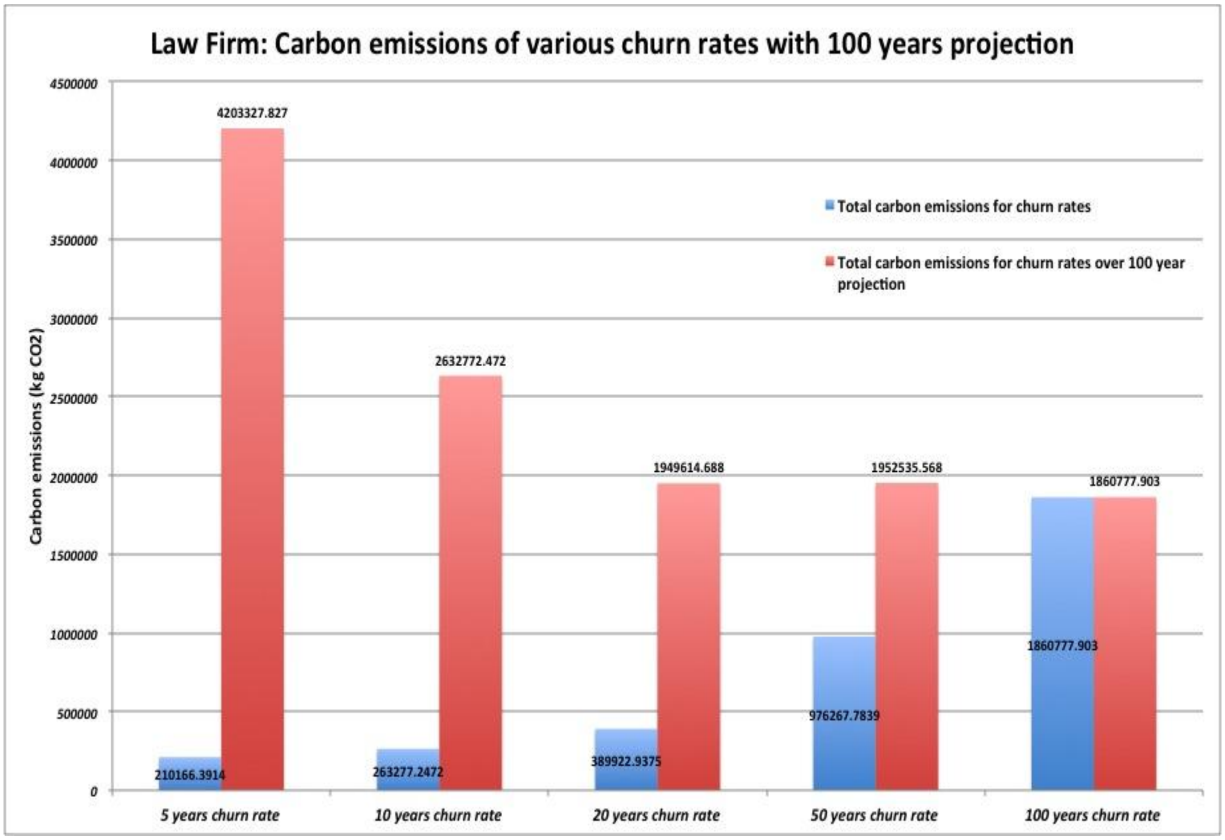


Figure 9. In this graph, the impacts of various churn rates (represented in blue) are compared side by side over a hypothetical 100 year period (represented in red). The blue bar represents the impact of one churn of a set of materials, and the red bar graph coupled with it represents the total amount of carbon or energy embodied over a 100 year period due to that churn rate. For example, the first blue bar graph displays the impact of a five year churn rate in five years, or one churn. Alongside it, the impact associated with that churn rate over 100 years is shown, and is therefore twenty times the amount of the blue bar graph.

6.3. Hotel Scenarios

All nineteen hotel scenarios are described in Table 4 above. Scenarios 1 – 16 evaluated the carbon and energy impacts by materials alone. The effect of churn rate is introduced in Scenarios 17, 18, and 19. Scenarios 17, 18, and 19 all originate from Scenario 1 (structured after a standard hotel room), in that this baseline hotel room setup now incorporates churn rates of five, ten, and twenty years, respectively.

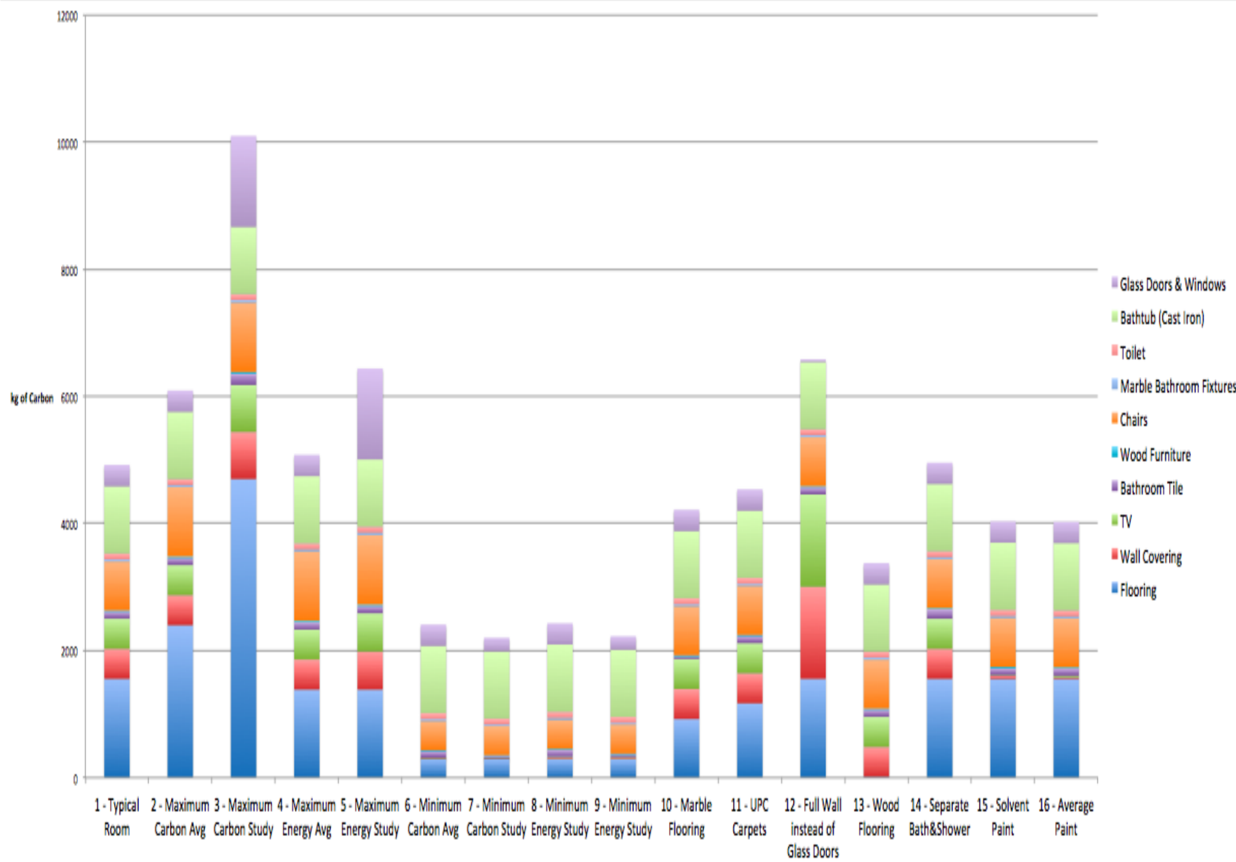


Figure 10. A compilation of the all of the scenarios by their total kilograms of carbon emissions. The full bar represents each scenario's total carbon content, with each individual material represented by a different color compiling the full bar. Scenarios 17, 18, and 19 were excluded so as not to skew the data.

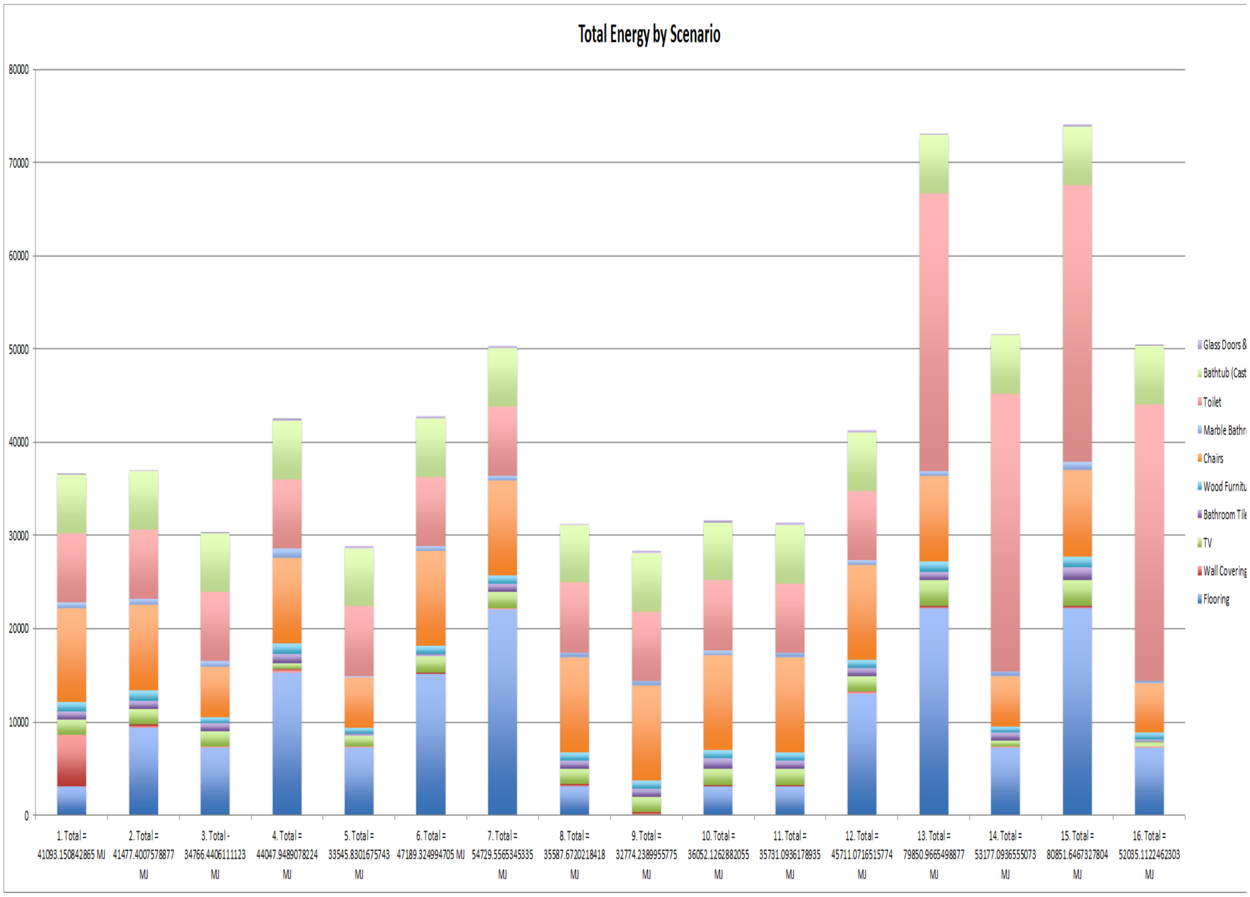


Figure 11. A compilation of the all of the scenarios by their MJ of energy used. The full bar represents each scenario's total energy use, with each individual material represented by a different color compiling the full bar. Scenarios 17, 18, and 19 were excluded so as not to skew the data.

6.3.1 Best Time Frame

As displayed in Table 6 below, Scenario 19, which integrates the lowest, or least frequent churn rate, results in the smallest overall carbon and energy impacts per room. Regardless of churn rate, the total amount of energy is much greater than carbon. The energy is several times larger than carbon for all three. The amount of decrease is the more dramatic for energy than for carbon. As you can see, energy decreases by an entire magnitude, from 366,658.39 MJ to

78,856.56 MJ, when churn rate is changed from 5 to 20 years. On the contrary, carbon does not. It only decreases from 48,443.53 kg CO2 to 14,533.06 kg CO2.

Table 6. Churn rate scenarios 17-19: The total carbon and energy impacts per standard hotel room resulting from the consideration of five-, ten-, and twenty-year churn rates.

Scenario	Total Carbon Impact [kg CO_2/Room]	Total Energy Impact [MJ/Room]
17: Five-Year Churn Rate	48,443.53	366,658.39
18: Ten-Year Churn Rate	24,221.77	183,329.20
19: Twenty-Year Churn Rate	14,533.06	78,856.56

6.3.2 Worst Time Frame

Table 6 shows that Scenario 17, which has a more frequent churn rate of five years, results in the greatest overall carbon and energy impacts per room. Unfortunately, such a short time frame may be more of the rule than the exception. The reason is because since hotels need to have a high standard of the appearance of their rooms, and components may get replaced far earlier than their expected lifetime. Where in an office, it may be more acceptable to have normal wear and tear on the components. Another aspect to consider is that people are less likely to be mindful of damage they cause in hotel rooms, and with so many people moving in and out of the rooms on a daily basis, the wear and tear can add up very quickly.

6.3.3 Materials by Scenario

Scenarios 1 through 16 do not consider material lifetimes and churn rate, but instead focus on the energy embodied in a standard hotel room, based only off of the embodied energy within each material. So, when material impact alone is considered, chairs and bathtubs stand out as the materials with the greatest relative impacts in Scenarios 1, 2, 3, 6, and 7.

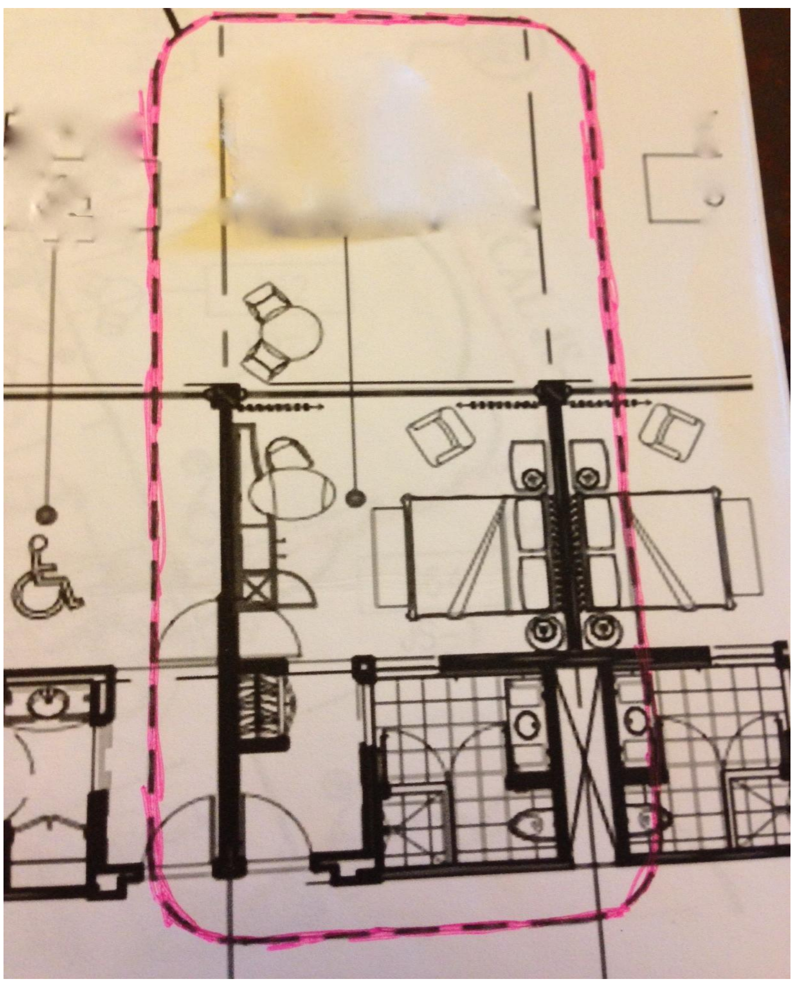


Figure 12. Snapshot of the blueprint of the standard hotel room designated in this study.

Scenario 1, or the baseline hotel scenario (see Figure 12 above), is structured based off of the materials that would be found in the standard hotel room sampled in this study. The changes in material choice or churn rate are evaluated in relation to this baseline scenario. The results are shown below in Figure 13. The results of other scenarios can be found in Figures 25A through 25P of Appendix C.

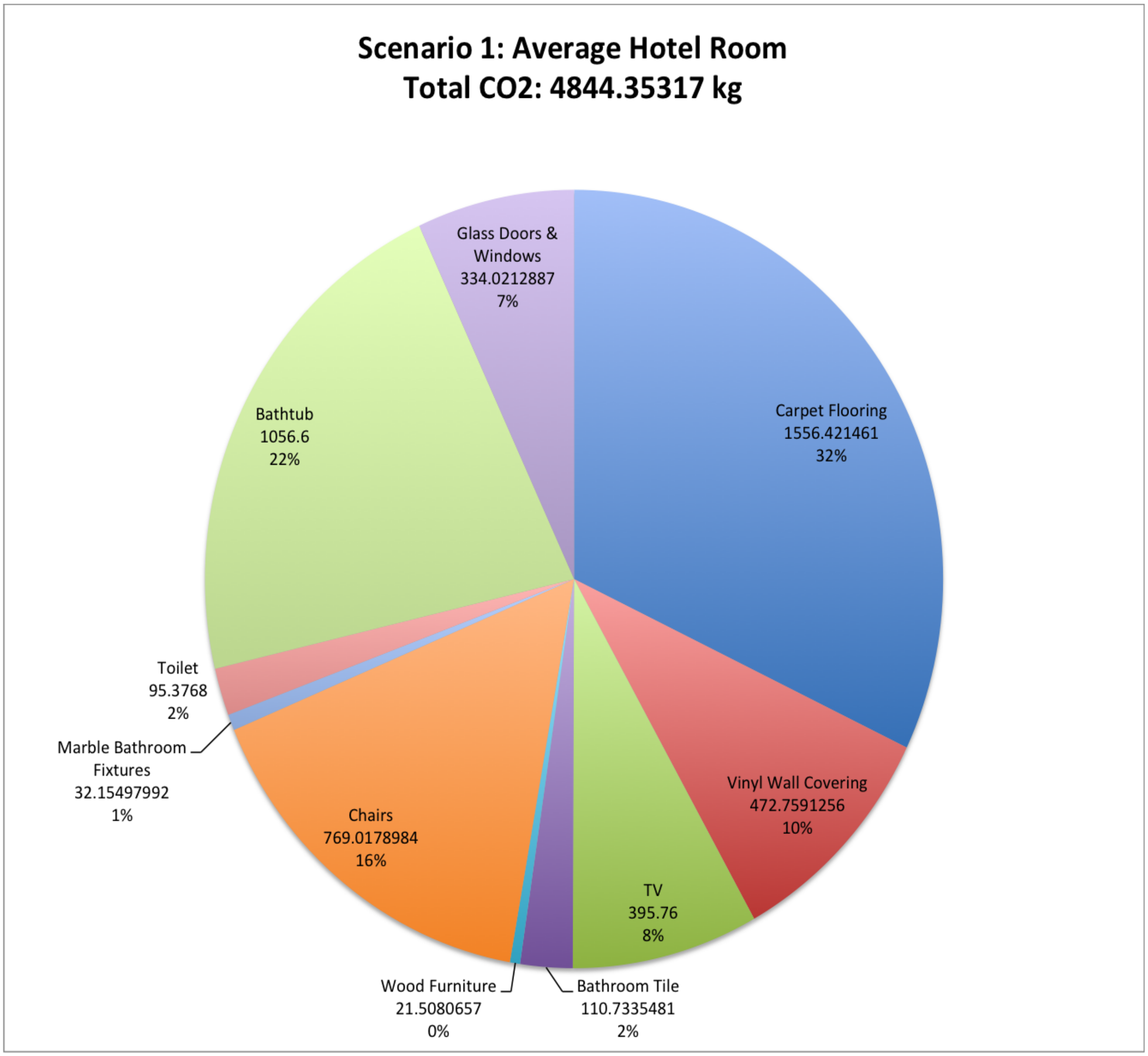


Figure 13. Scenario 1, our base scenario. This was developed based on the current materials and furniture in the hotel room.

Scenario 3 is the worst-case scenario, in terms of carbon impact. The highest carbon result from a single study across each material category is used to determine which material's data will be used to calculate the hotel room's embodied energy and carbon. Therefore, this scenario is a worst-case scenario in terms of carbon impact, as materials are selected depending on if they are the highest contributors of embodied carbon.

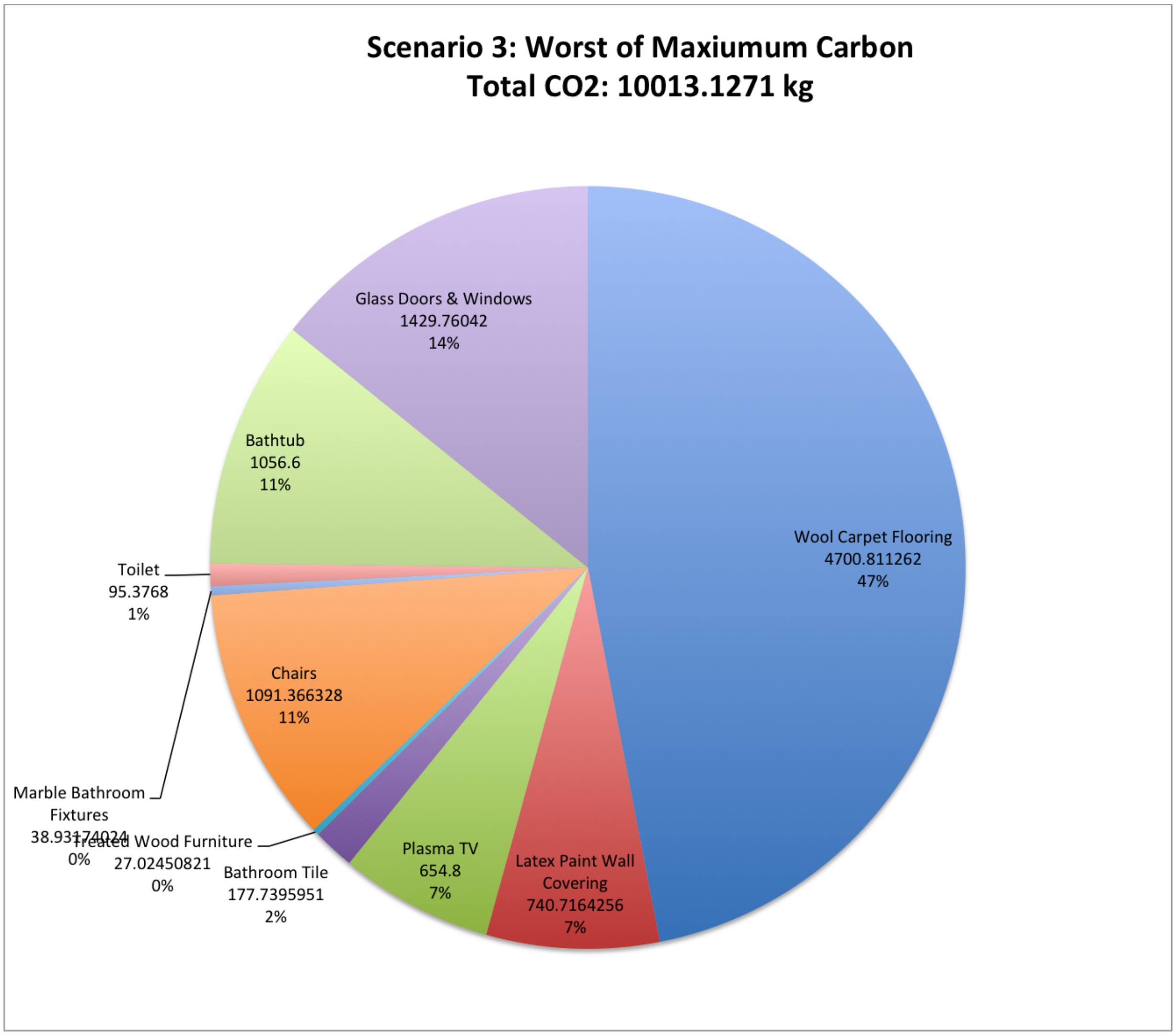


Figure 14. Scenario 3 - A worst-case scenario determined in terms of maximum embodied carbon per material. We took the highest, most carbon intensive study from each highest average to construct the absolute "worse case scenario".

Other scenarios are analyzed based upon the difference between themselves and Scenario 3, and this difference is represented by a white portion displayed in figures allowed us to conclude with several observations, one of which is not often considered in typical renovations. Wood flooring was a clear choice as the flooring material with the lightest impact, as it is only represented by a sliver in Scenario 13 (See Figure 15 below). When the materials with the smallest carbon and energy impacts are selected , the change in overall impacts of the Scenarios 7 (best studies based on carbon) and Scenario 9 (best studies based on energy) are fairly similar in their overall eductions relative to Scenario 3, or the worst-case scenario.

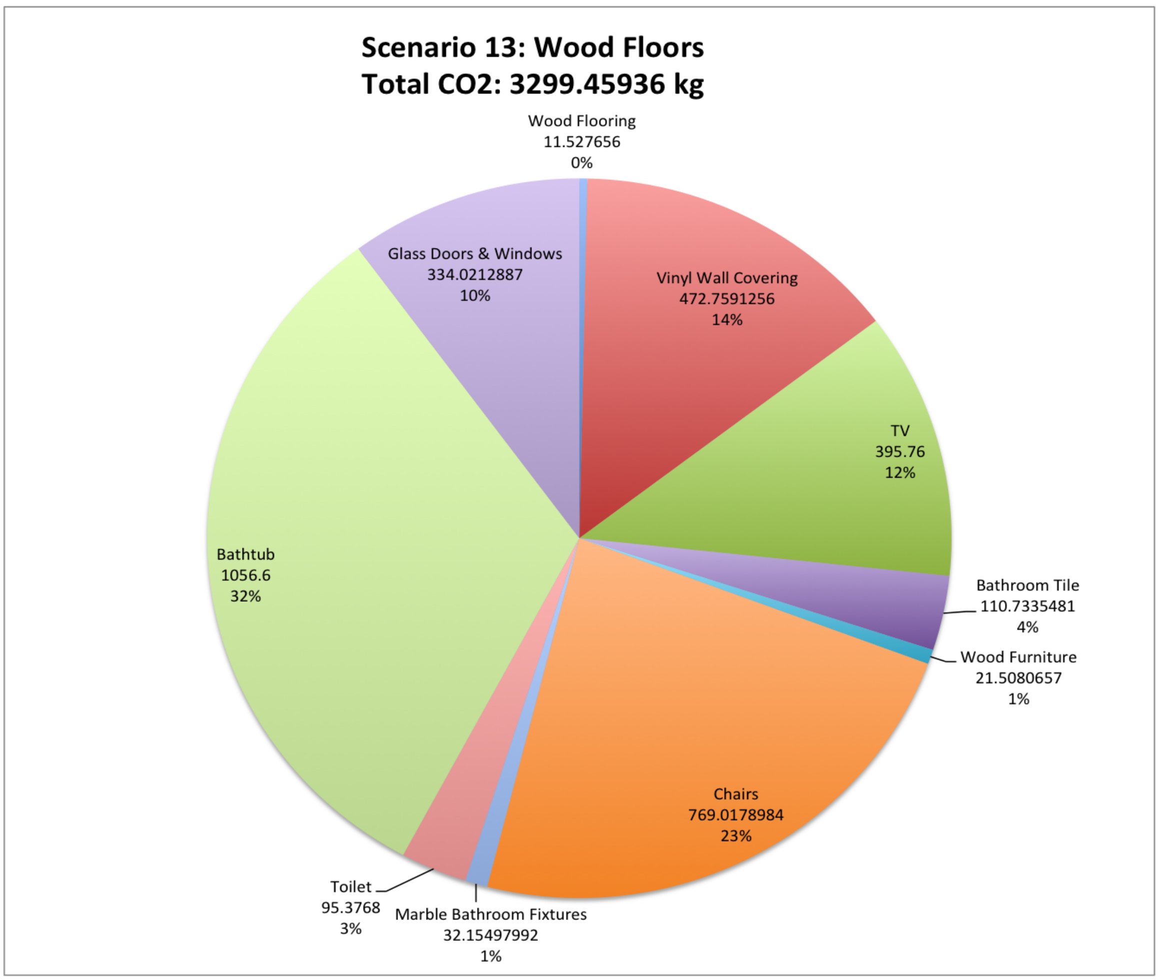


Figure 15. Scenario 13 was compiled by replacing the carpet flooring in the bedroom with wood flooring.

Differences in paints selected did not do much to change the overall impact of a scenario, observed in Scenarios 5, 6, 15, and 16 (Refer to Figures 25E, 25F, 25O, and 25P, respectively in Appendix C), despite their high range of variation across paint type and literature source. Finally, Televisions, which are often overlooked by those conducting typical renovations, were shown to have a significant impact relative to other materials in Scenario 8 (See Figure 16 below). Scenario 8 selected its materials by their lowest energy averages, and when all of these materials are shown at their best averages, TVs stood out as taking up a large relative portion of the impact, allowing us to conclude that the energy impact to create a low-carbon TV is not necessarily a low one. Therefore TVs, should be evaluated more carefully before they are purchased in bulk quantities.

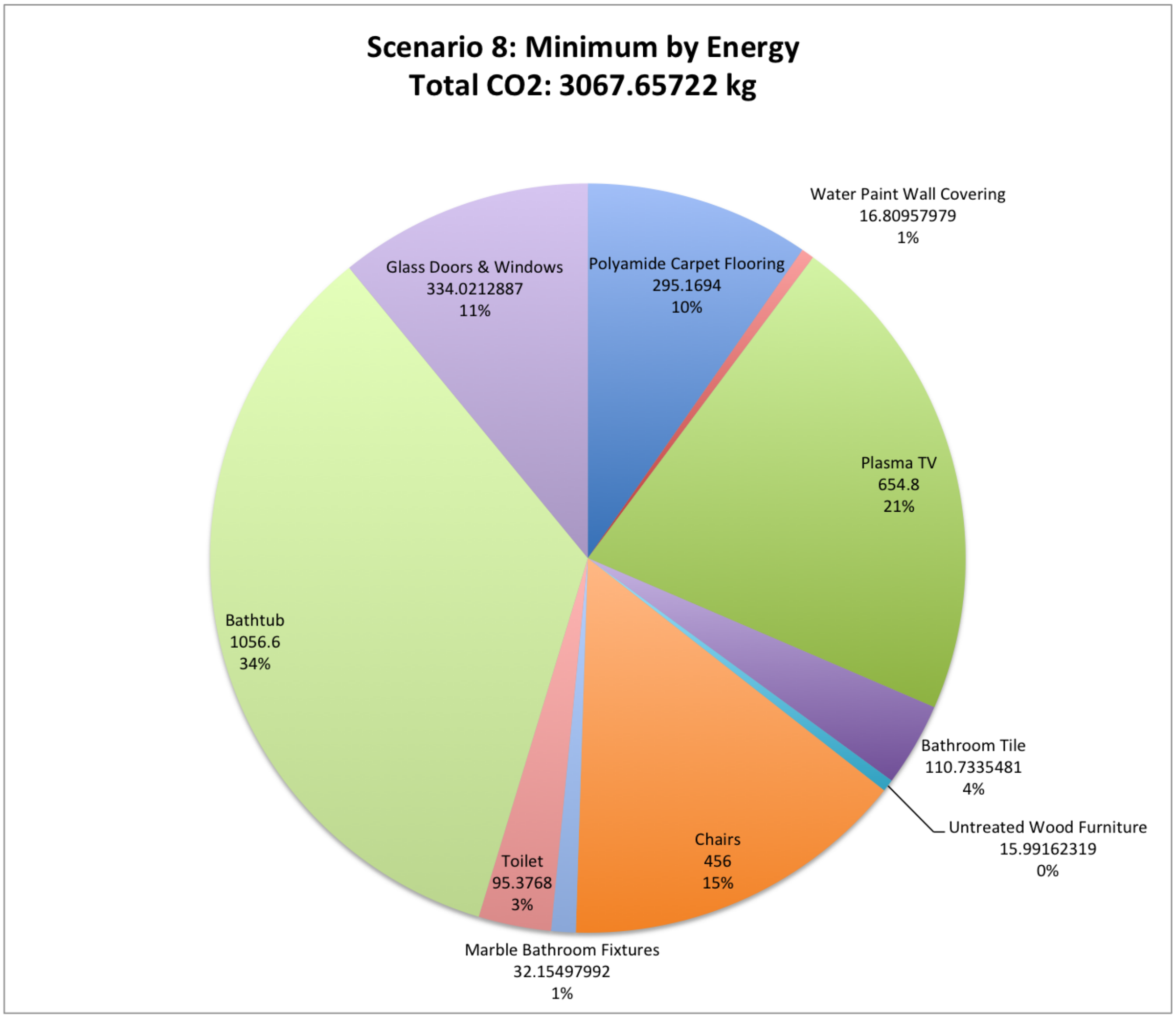


Figure 16. Scenario 8 was created from the values for the minimum energy material average in each category.

Of the wall coverings studied, solvent-based paint and vinyl covering have the greatest impact; whereas latex- and water-based paints have the least. However, churn rate and material lifetime must be considered as well, to determine whether the durability of a material can make that material a desirable choice if it is able to bring about a long-term reduction in the carbon and energy impact. For example, Scenario 6, which assumes that its latex-based paint is refreshed at a frequency solely dependent upon its typical lifetime, has an average energy impact of 148.17 MJ per hotel room. Over a fifty year period, this paint would theoretically be refreshed thirteen times (based upon its theoretical lifetime of four years), resulting in a total impact of 1,926.21 MJ per room. Comparing this scenario to Scenario 19, with its low churn frequency of twenty years (and therefore three theoretical vinyl wall covering refreshes over a fifty year period), we find that it still has a smaller overall energy impact, despite the refreshes in Scenario 6 occurring more than four times as often as those of Scenario 19. In this case, durability and its resultant churn rate are not sufficient to offset the high amount of embodied energy present in vinyl wall coverings.

Wood and polyamide carpets are among the more sustainable floor coverings, whereas marble, wool carpet, and UPC carpet have larger impacts. This finding is best observed in Scenarios 13, 10, and 11. Scenario 13 is constructed with wood as its principal bedroom floor covering, and as expected from Figures 1 and 2 above, and the flooring impact of the bedroom is the lowest in terms of both carbon and energy, across all scenarios. In Scenario 10, marble flooring is introduced as the floor covering, resulting in a greater energy impact than the scenarios that were constructed with polyamide carpet and wood flooring, but still lower than scenarios using wool and UPC carpets. The embodied energy present in flooring material for this scenario was more than twice the amount of scenarios constructed with polyamide carpets (Scenarios 6 through 9), and over 200 times greater than the embodied energy of the wood flooring used in Scenario 13.

Scenario 11 represents the highest flooring energy impact out of Scenarios 1 through 16, in its use of UPC carpet as the floor covering. However, when the carbon impact of UPC flooring is compared to other scenarios, it is no longer the cause of the highest carbon flooring impact, which is instead observed in Scenario 3, which utilizes wool carpet.

Table 7 below summarizes the scenarios that had the lightest and heaviest carbon and energy impacts in terms of flooring and wall covering. The materials causing the highest and lowest impacts almost perfectly correspond across energy and carbon units, except in the case of the highest floor impact. In this case, wool carpet causes the highest carbon flooring impact, but UPC carpet causes the highest energy impact.

Table 7. High and low carbon and energy impacts associated with Scenarios 1 – 16 and their selected flooring and wall covering materials. The high and low impact values for each material category are also compared in a ratio format.

Carbon Impact	**Highest floor carbon impact**	**Lowest floor carbon impact**	**Greatest impact: Smallest impact**	**Highest wall covering carbon impact**	**Lowest wall covering carbon impact**	**Great est impact: Smallest impact**
Scenario	3	13	Ratio*	12	7	Ratio*
Material used	*Wool Carpet*	Wood (average)	407.7:1	Vinyl wall covering (average)	Latex-based paint	555.78:1

Energy Impact	**Highest floor energy impact**	**Lowest floor energy impact**	**Greatest impact: Smallest impact**	**Highest wall covering energy impact**	**Lowest wall covering energy impact**	**Greatest impact: Smallest impact**
Scenario	5, 6	13	Ratio*	12	7	Ratio*
Material used	*UPC carpet*	Wood (average)	323.73:1	Vinyl wall covering (average)	Latex-based paint	74.02:1

6.3.4 Average, Maximum, and Minimum

As displayed by the ratios featured in Table 7 above, the differences between the minimum and maximum impact values were very large for both CO_2 and energy. These ratios highlight the wide range of energy and carbon values that were encountered during the literature search. The variability of CO_2 is slightly larger than that of energy, most likely because it could be more difficult to obtain exact measurements of CO2 in comparison to energy. For example, CO_2 emissions from extracting raw materials and manufacturing are more difficult to accurately quantify than tallying up energy usage from electrical consumption audits.

7. Discussion

7.1. Materials

7.1.1. Best Materials

We have concluded that wood is our primary recommendation for flooring material because it has the lowest embodied energy. If wood does not fit the building design or is not aesthetically pleasing to the owners/tenants, we would recommend either ceramic tile or linoleum when not considering churn rate. However if churn rate is taken into consideration, we would recommend wood, ceramic tile, and marble. If carpets must be used, carpet tiles could be a promising alternative, as there are several manufacturers that have a recycling program in which customers can send back used carpets to be recycled. In addition, if a carpet is damaged in one area, the damaged tiles can be removed and replaced, while the rest of the carpet can be left in place, allowing the carpet to have a longer lifetime. For wall coverings, our primary recommendation is paint as it has the lowest carbon and energy intensities. Vinyl is recommended as a second option because of its long lifetime of 40 years.

7.1.2. Worst materials

We have concluded that carpet and linoleum should be considered last when possible because they are relatively high energy and high carbon materials. Another material that we would not recommend is glass as wall coverings. Although glass has a longer lifetime than its alternative, paint, glass is very energy intensive. We also have saw that chairs and TV/computer monitors were amongst the most carbon and energy intensive materials, but cannot make a specific recommendation to prevent the use of these bulk item materials. As mentioned above we do acknowledge that the reason these bulk items are so carbon and energy intensive is because an office space requires so many chairs and TV/computer monitors. Our recommendation would be to seek a company that is focused on supplying these items at a lower environmental cost since these items make up such a large proportion of the total environmental costs.

7.2. Office Scenarios

7.2.1. Best Time Frames

As displayed in Figure 9, the amount of CO2 begins to level off at a 20-year churn rate. It would be best for tenants to have at least 20-year leases to minimize CO2 emissions. This is true for energy as well (see Figures 22A through 22C in Appendix B). When the time between leases is increased to 50 and 100 years, the decrease in impact barely improves, making leases this long marginally rewarding. Regardless, it is not very realistic to have such long leases.

7.2.2. Worst time frame

As shown in Figure 9, the difference between the renovations over 5 years (blue bar) and the total over 100 year with a time frame of 5 years (red bar) was the greatest. This is because the churn rate was so high (simulating continual 5 year leases over 100 years). This means that many components get changed prematurely, since they have a longer longer lifetime. Other than televisions, computers, and paint, all other components have a lifetime larger than 5 years. Since a majority of materials are being changed prematurely over 100 years, the CO2 adds up quickly since this happens 20 times. For the other churn over rates, the amount of times components get changed prematurely is several times less. Most materials with high amounts of CO2 are able to last on average longer than 10 years. Therefore, the blue bar doesn't increase as quickly until it reaches the 20 year mark. Quintessentially, the significant proportion between the two bars indicates that 5 years is clearly the worst time frame. As expected, a very high churn rate would be much worse on the environment with a greater use of materials.

7.2.3. Materials by Scenario

The most costly components in regards to CO_2 when lifetimes are taken into consideration are computers and carpet. The reason is most likely because of the sheer amount of carpet and the number of computers. When lifetimes are considered over the course of 20 years (scenario 1), the most costly in regards to CO_2 is computers. This is likely due to the number of them and their short lifetime of 4 years.

On the contrary to CO_2, the most costly component in regards to energy was chairs when lifetime is considered over the course of 20 years (scenario 1). Similar to the case of computers and carpets, this may also be due to the number of chairs needed in an office floor.

Between the scenarios that had a material change (scenarios 4-6), the only material change that had a significant decrease was carpet to wood flooring and this decrease was seen in energy, but not CO_2. This decrease is most likely due to both the fact that wood has lower embodied costs and that wood is more durable and has a much longer lifetime.

In regards to CO_2, a change that created a significant increase in total CO_2 was changing 50% of the painted walls to glass. This may be due to the glass being more durable and the 20 year time frame being too short to capitalize on it. In regards to energy, a material change that created a significant increase in total energy for entire floor was changing the flooring from carpet to marble. This may be because marble is more durable than carpet and the 20 year time frame is too short to capitalize on it.

When churn rate is considered, carpet and computers stand out among the other components. As the churn rate decreases, the percent contribution of computers goes up for a majority of the scenarios. This is most likely due to there being so many of them and its short lifetime. As the churn rate decreases the percent contribution of carpet decreases for both CO_2

and energy. This may be because of the percent contribution of computers increasing with decreased churn rate.

7.2.4. Average, Maximum, and Minimum

The difference between the minimum and maximum was very large for CO_2. For both floors it was about 10 to 20 times larger. This is may be a testament to the variability in CO_2 data. The variability of CO_2 is larger than energy because it may be harder to get exact measurements of CO_2 in comparison to energy. For instance, the CO_2 emissions from extracting raw materials and manufacturing is more difficult to account for than the MJ from electricity used.

7.2.4 Overall Office Recommendations

We recommend that the best way to lower the contribution of computers is for computer designers to invest more in developing computers with far greater durability. One idea is allowing the computer to be more able to be updated and modified as technology rapidly changes every year, instead of having to get an entire new computer.

In regards to carpet, it is best to have less frequent tenant changes to avoid changing the carpet prematurely. Since this is not the reality at times, it may be a good idea for carpet manufacturers to look into designing carpet that can be modified and repaired, so that it will be appealing to a new tenants to keep the carpet instead of replacing it prematurely. Also, it would be best to change to the wood flooring instead of using carpet, due to its low embodied costs and high durability.

Since the total amounts of CO_2 and energy begin to level off at 20 years, we would encourage property owners to establish leases of 20 years or longer. Although this is not always feasible in every industry, this would minimize the effects of premature renovations of the office floor. Economic incentives that benefit both the building owner and the tenants may provide for the motivation to do this.

7.3 Hotel Scenarios

7.3.1 Best and Worst Time Frames

As stated earlier, the most sustainable churn rates are those that are less frequent. Whether a less frequent churn rate can be achieved; however, is dependent upon the material's durability and ability to offset the high impact that is often associated with durable materials such as vinyl wall coverings. In addition, hotels tend to be refreshed more frequently than 20 years, usually on the scale of ten to twelve years between refreshes. Therefore, durability may not be able to be applied to achieve long term savings if durable materials are being prematurely disposed of due to style and hotel rating changes.

Churn rate and material lifetime must be considered to determine whether the durability of a material can make that material a desirable choice and if it is able to bring about a long term reduction in the carbon and energy impact. For example, Scenario 6, which assumes that the latex-based paint is refreshed at a frequency solely dependent upon its typical lifetime, has an average energy impact of 148.17 MJ per hotel room. Over a fifty year period, this paint would theoretically be refreshed thirteen times (based upon its theoretical lifetime of four years), resulting in a total impact of 1,926.21 MJ per room. Comparing this scenario to Scenario 19, with its low churn frequency of twenty years (and therefore three theoretical vinyl wall covering refreshes over a fifty year period), we find that it still has a smaller overall energy impact, despite the refreshes in Scenario 6 occurring more than four times as often as those of Scenario 19. In this case, durability and its resultant churn rate are not sufficient to offset the high amount of embodied energy present in vinyl wall coverings.

When comparing carbon and energy for churn rates, it was found that energy had a much more dramatic decrease with changing churn rates than carbon. This is most likely due to energy being many times larger than the carbon emitted for all components. As a result, the most efficient way to lower the environmental impact when considering churn rate may be to focus on the components that have the highest energy usage.

7.3.2 Best and Worst Materials

While various paint types are shown to vary significantly in comparison to each other, as stated earlier, only a slight change (about 1 percent) in the relative carbon footprint due to paint is observed. Therefore, water and latex -based paints are still the most sustainable, but they are not necessarily the material that should be expected to result in dramatic savings in carbon and energy. It is more environmentally productive to avoid wall coverings that have a significantly greater impact, such as vinyl wall coverings. Wood floors, however, show large relative decreases when they are introduced (in Scenario 13), relative to the baseline scenario. A sharp decline in embodied carbon is also observed due to incorporating polyamide carpets in the baseline hotel room.

7.3.3 Overall Hotel Recommendations

In evaluating these scenarios, we recommend that hotels conduct large-scale renovations every twenty years, to achieve the highest carbon and energy savings, if durability is a priority. The materials that we recommend to be used over this longer churn rate are vinyl wall coverings, and any durable wood, carpet, or stone flooring material. However, as several scenarios demonstrated, even durability over the long run can be inadequate in its ability to produce long term energy and carbon savings. If the design priorities of the hotel are more directed toward lowering initial embodied costs rather than durability, we recommend that hotels utilize wood or polyamide carpets as their flooring materials, and water- or latex-based paints for wall coverings.

According to observations made by our clients regarding their hotel renovation experiences, hotels tend to refresh their materials at a rate more frequent than twenty years (typically every ten to twelve years). This is in order to stay competitive with new hotels and other hotels with similar ratings. Hotels focused on improving their sustainable image should avoid materials such as wool and UPC carpets, as well as solvent-based paints and vinyl wall coverings, as these materials are very carbon and energy intensive. Similar to what we suggested for office floors, hotels can also possibly consider modular carpet tiles that can be replaced in only the areas that are damaged or stained to help prolong the lifetimes of these materials. This may be especially beneficial in hotels since they experience so much wear and tear from their guests. We also have observed that the energy impact to create a low-carbon TV is not necessarily a low one. Therefore, TVs should be evaluated more carefully before they are purchased in bulk quantities.

8. Conclusion

After our extensive research and material comparisons, we are able to make recommendations on the most and least sustainable materials, as well as the best churn rate to maximize the materials. Wood is the most sustainable flooring material and paint is the most sustainable wall covering. Vinyl is an alternative for wall coverings when durability is important due to its longer lifetime. We highly recommend to stay away from using linoleum due to its high carbon intensity as well as glass, due to its high energy intensity. We recommend setting the churn rate for both hotel and office spaces to 20 years in order to maximize the energy and carbon savings by utilizing material durability.

Unfortunately, it is difficult to implement these changes because they must renovate often to stay competitive and because commercial landlords often do not have customers who are willing to sign leases that are 20 years or longer. We encourage office tenants and hotel owners to consider durability and lifetime of products when choosing their materials. Perhaps future motivation can come from green certifications or economic incentives

9. Recommendations/Limitations

During our research we encountered some limitations that may introduce some uncertainty to our results and analyses. First, during data collection for the material database, the data sources differed in several aspects. Some materials had more abundant LCA literature focusing on them, and of these sources, some articles provided embodied energy, carbon, or both. In the sources that only provided one of these data points, we utilized a conversion factor to interpolate missing energy or carbon data (see Section 5.5 Assumptions). Therefore, some of our sources show a correlation between carbon and energy due to our estimations of carbon or energy via conversion factors, while sources that reported both carbon and energy do not necessarily always show the same relationship.

Our sources also differed in their individual methodologies, as some are independent academic articles published to journals, while other data came from databases such as BEES and NREL. Various reports also differed in how they presented their results. Some presented results by each section of the life cycle, while others only provided an overall value. Energy mix also had an effect on our results, as our reports are based in locations all over the world, and every location has a different composition of energy sources, which can cause differences in results for the one material. The differences in academic coverage, data offered, their methodologies and results, and their geographic location create some uncertainty in our averages for each material.

This uncertainty can be seen in the margin of error featured in Figures 1 through 6. The error bars show the minimum and maximum data points of each material.To avoid this issue and ensure the success and improved accuracy of future life cycle studies, we recommend that future LCA and LCI studies develop a uniform methodology, so that various studies can be collectively analyzed for more accurate estimations.

In terms of assumptions of churn rate, we must note that decisions to renovate and refresh hotels and offices differ by hotel or building owner. Our churn rate assumptions and investigations are based off of commonly observed timeframes in hotel and office building types that were obtained during interviews with our client.

We recommend that future studies be conducted on materials that are not widely covered in scientific literatures, such as bathtubs and doors. We also noticed a significant lack of information on multi-material components such as mattresses and couches. In structuring our scenarios, we had to make some rough estimates due to this lack of information. We also feel that it would be very beneficial for manufacturers to do further study regarding the possibility of modular tiled carpets, as this could be useful to the commercial and hospitality sectors as well as the residential sector.

The various impacts associated with different materials as they enter the landfill phase of their life cycle is also another area of interest that should be covered in future reports. For example, mattresses and different types of paint differ in their impacts upon disposal, and in most renovations, these materials are typically landfilled as they are no longer reusable. A study that surveys the renovation materials that are most commonly landfilled, recycled, reused, or incinerated could be a useful resource for construction managers, building owners, and other building and business and stakeholders that are interested in sustainability.

9. Works Cited

Aksamija, A. 2010. Comparative analysis of flooring materials. Perkins+Will Research Journal **2(1)**: 55-66.

Andrae, A. S. G., and O. Anderson. 2010. Life cycle assessments of consumer electronics - are they consistent?. International Journal of Life Cycle Assessment **15:** 827-836.

Asif, M., T. Muneer, and R. Kelley. 2007. Life cycle assessment: a case study of a dwelling home in Scotland. Building and Environment **42(3)**: 1391-1394.

Basbagill, J., F. Flager, M. Lepech, and M. Fischer. 2013. Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. Building and Environment **16:** 81-92.

Beetsma, J., and A. Hofland. 1998. Life cycle analysis of alkyd emulsion based paint. Surface Coatings International **10:** 491-494.

Bowyer, J., S. Bratkovich, and F. Fernholz. 2009. Life cycle assessment of flooring materials. Dovetail Partners Inc. Available from http://www.dovetailinc.org/files/DovetailFloors0809.pdf.

Buchanan, A. H., and S. B. Levine. 1999. Wood-based building materials and atmospheric carbon emissions. Environmental Science & Policy **6**:427-437.

Celebi, U. B., and N. Vardar. 2008. Investigation of VOC emissions from indoor and outdoor painting processes in shipyards. Atmospheric Environment **42:** 5685-5695.

Chen, T. Y., J. Burnett, and C. K. Chau. 2001. Analysis of embodied energy use in the residential building of Hong Kong. Energy **26(4)**: 323-340.

Cole, R. J., and D. Rousseau. 1992. Environmental auditing for building construction: energy and air pollution indices for building materials. Building and Environment **27(1)**: 23-30.

Dobson, I. D. 1996. Life cycle assessment for painting processes: putting the VOC issue in perspective. Progress in Organic Coatings **27:** 55-58.

Guo, H., F. Murray, S.C. Lee, and S. Wilkinson. 2004. Evaluation of emissions of total volatile organic compounds from carpets in an environmental chamber. Building and Environment **39:** 179-187.

Hischier, R., and I. Baudin. 2010. LCA study of a plasma television. International Journal of Life Cycle Assessment **15:** 428-438.

Hubbard, S. S., and S. A. Bowe. 2008. Life-cycle inventory of solid strip hardwood flooring in the eastern United States. Available from http://www.corrim.org/pubs/reports/2010/phase2/Module_E.pdf

Jonsson, A., A. M. Tillman, and T. Svensson. 1997. Life cycle assessment of flooring materials: case study. Building and Environment **32(3)**:245–255.

Kofoworola, O. F., and S. H. Gheewala. 2008. Environmental life cycle assessment of a commercial building in Thailand. International Journal of Life Cycle Assessment **13:** 498-511.

Lippiatt, B., A. L. Greig, and P. Lavappa. 2011. BEES (building for environmental and economic sustainability). The National Institute of Standards and Technology. Available from http://www.nist.gov/el/economics/BEESSoftware.cfm.

Michaelis, P., T. Jackson, and R. Clift. 1998. Energy analysis of the life cycle of steel. Energy **23**:213–220.

Nebel, B., B. Zimmer, and G. Wegner. 2006. Life cycle assessment of wood floor coverings - a representative study for the German flooring industry. The International Journal of Life Cycle Assessment **11(3):**12-182.

Nicoletti, G. M., B. Notarnicola, and G. Tassielli. 2002. Comparative life cycle assessment of flooring materials: ceramic versus marble tiles. Journal of Cleaner Production **10**:283–296.

Papasavva, S., S. Kia, J. Claya, and R. Gunther. 2002. Life cycle environmental assessment of paint processes. Journal of Coatings Technology **74(925):** 65-76.

Petersen, A. K., and B. Solberg. 2004. Greenhouse gas emissions and costs over the life cycle of wood and alternative flooring materials. Climate Change **64:**143–167.

Potting, J., and K. Blok. 1996. Life-cycle assessment of four types of floor covering. Journal of Cleaner Production **3(4)**:201–213.

Price, L., J. Sinton, E. Worrell, D. Phylipsen, H. Xiulian, and L. Ji. 2002. Energy use and carbon dioxide emissions from steel production in China. Energy **27**:429-446.

Sathre, R., and L. Gustavsson. 2009. Using wood products to mitigate climate change: external costs and structural change. Applied Energy **2**:251-257.

Scheuer, C., G. Keoleian, and P. Reppe. 2003. Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. Energy and Buildings **35**:1049-1064.

Spitzley, D.V., B.A. Dietz, and G.A. Keoleian. 2006. Life-cycle assessment of office furniture products. Center for Sustainable Systems, University of Michigan Report No. CSS06-11.

Usbeck, V. C., J. Pflieger, and T. Sun. 2010. Life cycle assessment of float glass. Glass for Europe. Available from http://www.glassforeurope.com/images/cont/184_33890_file.pdf

Worrell, E., L. Price, and N. Martin. 2001. Energy efficiency and carbon dioxide emissions reduction opportunities in the US iron and steel sector. Energy **26**:513-536.

10. Appendix

10.1 Appendix A: Materials

17 (A)

	BEES		Literature Source #1	Literature Source #2	Literature Sou
Unit of Analysis			Garland chair	Siento chair	Airtouch
	Herman Miller Ambi	Generic Office Chair			
GWP (kg CO2 eqv)	272.841582	136.420791	218	114	
Energy (MJ)	2308.333333	2308.333333	3452	1350	

17 (B)

	unit	1-BEES: Generic Virgin Latex	2-BEES: Generic Consolidated Latex	3-BEES: Generic Reprocessed	1-Jotun Solvent	2-Jotun Solvent	3-Jotun Solvent
Carbon	kgCO2eq/m3	0.185703202	0.047915074	0.07318021	0.816611	0.75250311	0.77692523
Energy	MJ/m3	3.887148808	1.470522386	1.952659461	2425	979.95	2855.9
Water							
Values multiplied by the amount for new K-1		12.2487455	3.160416924	4.826872997	53.8626163	49.63414193	51.24499371
		256.3913598	96.99377429	128.7949186	159949.896	64636.24766	188371.5084
Values mulitplied for Scenario 8 (glass wall for balcony to painted wall)		14.66400135	3.783600371	5.778654812	64.48345896	59.42119738	61.34968325
		306.9476172	116.1193884	154.1912076	191489.446	77381.47736	225515.3438
	Unit: m^2			Senario 8 calculation	Scenario 11 calculation		
Area of Paint:	Total			7.704581214	7.704581214	CO2	
New JS1	104.049			176.6925671	176.6925671	energy	
Existing JS1	104.049						
Existing K1	65.95872						
New Hotel Room K-1	65.95872	13.006	78.96472				
Law Office Firm	17793						
Financial Services Firm: Wells Fargo Floor 54	963.22						
Creative Media Firm							
Total Office							

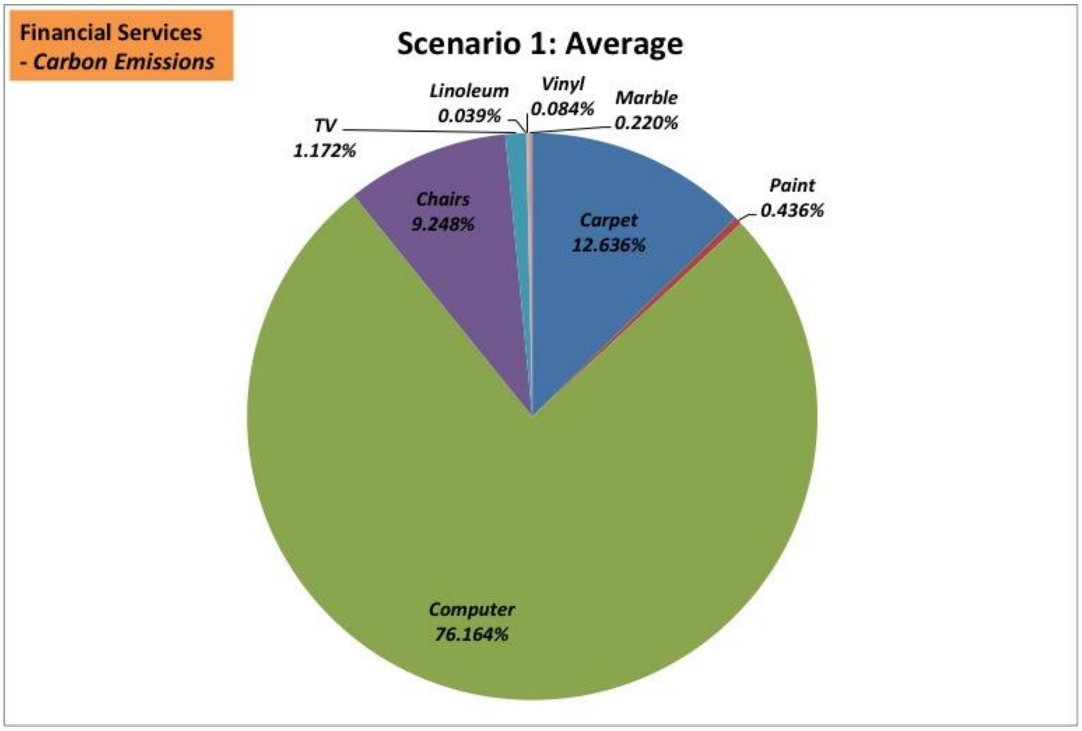
17 (C)

	unit	1-BEES: Nylon	2-BEES: Wool	3-BEES: Anonymous	4-BEES: UPC	Polyamide	Wool	Average	Avg woo
Carbon	kg CO2 Eq. per m^2	16.22434874	202.0985066	59.64243689	50.39917747	6.72	4.26	56.55741161	1
Energy	MJ per m^2	342.406	658.3874975	950.31	946.8441506	164.91	78.697	523.5924414	3
Water	liters								
Values multiplied by the amount for new K-1		377.3783517	4700.811262	1387.283082	1172.284868	156.3072	99.0876	1315.525394	2
		7964.36356	15314.09319	22104.2106	22023.59494	3835.8066	1830.49222	12178.76019	8
	Unit: m^2								
Area of Carpet:									
Existing JS1	33.44508								
Existing K1	23.226								
New Hotel Room K-1	23.26								
Law Office Firm: Morrison & Foerster	655.33								
Financial Services Firm:	11.148	wool	678.947						
Wells Fargo Floor 54	667.799	polyamide							
Creative Media Firm									
Total Office									

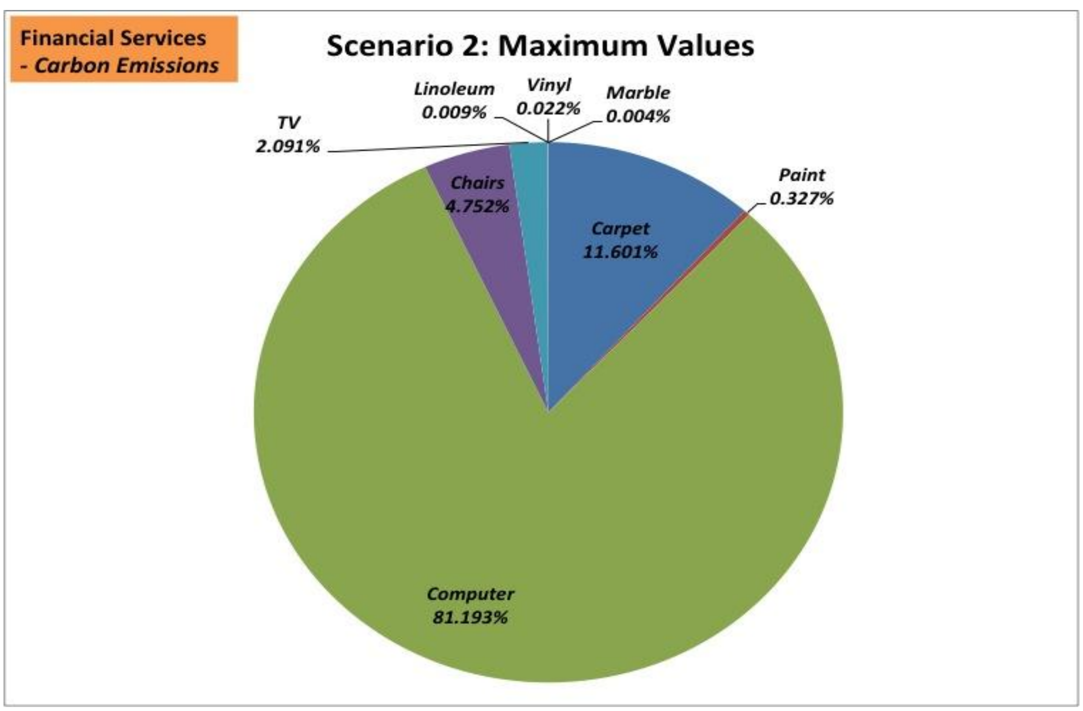
Figure 17. Screenshot of material database for (A) chairs (B) paint (C) carpet.

10.2 Appendix B: Office Scenarios

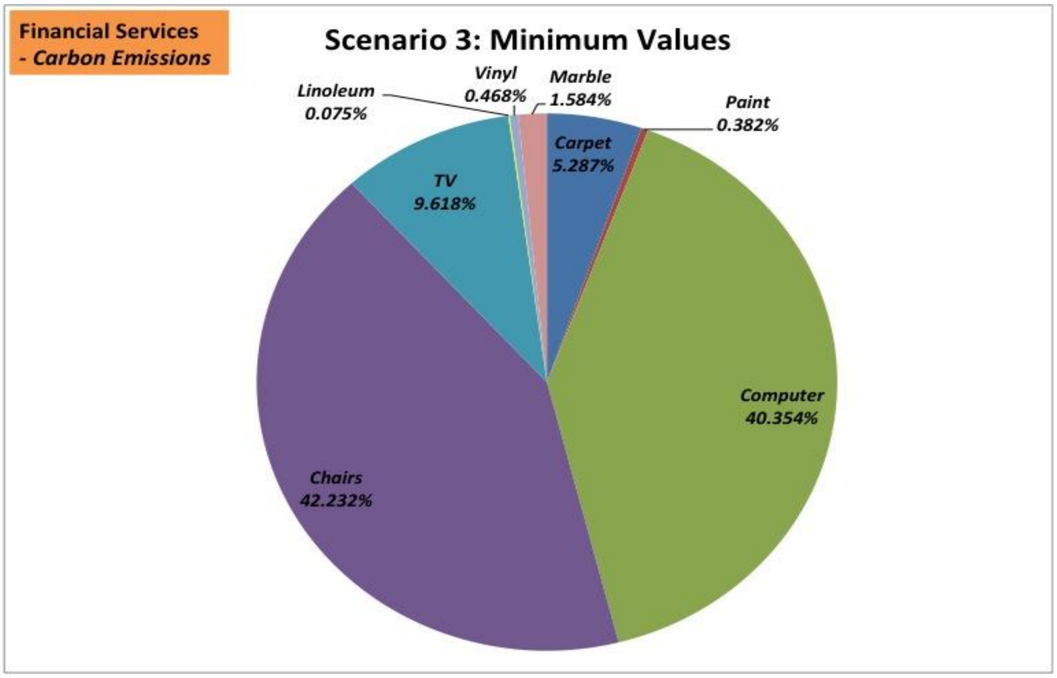
18 (A)



18 (B)

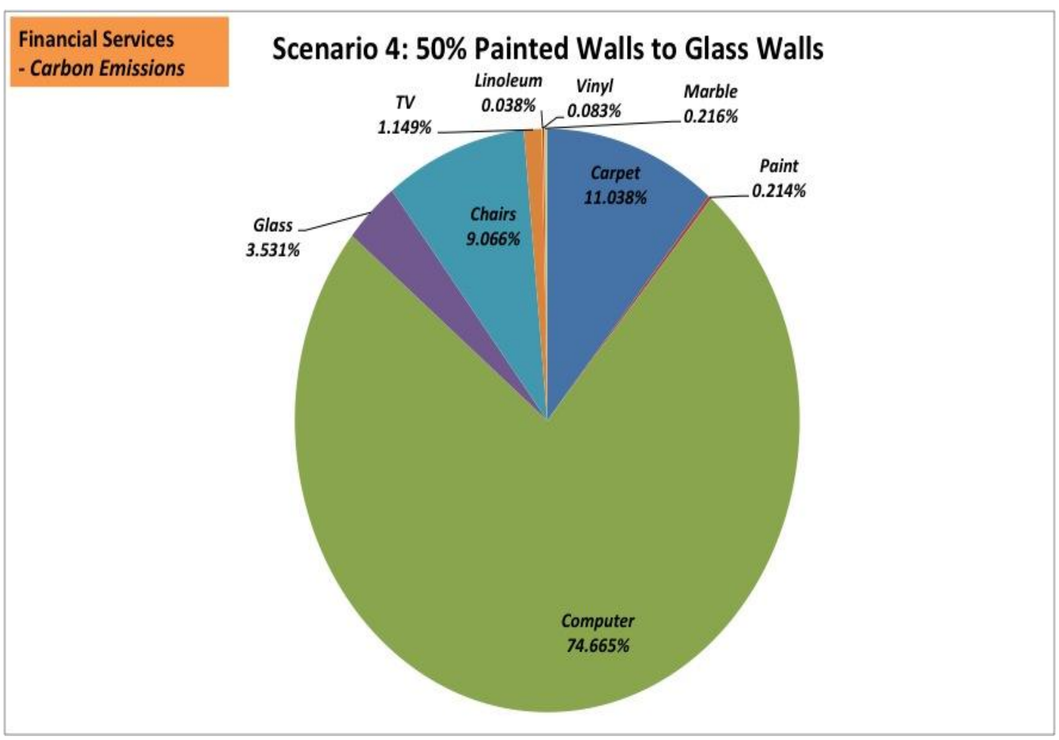


18 (C)



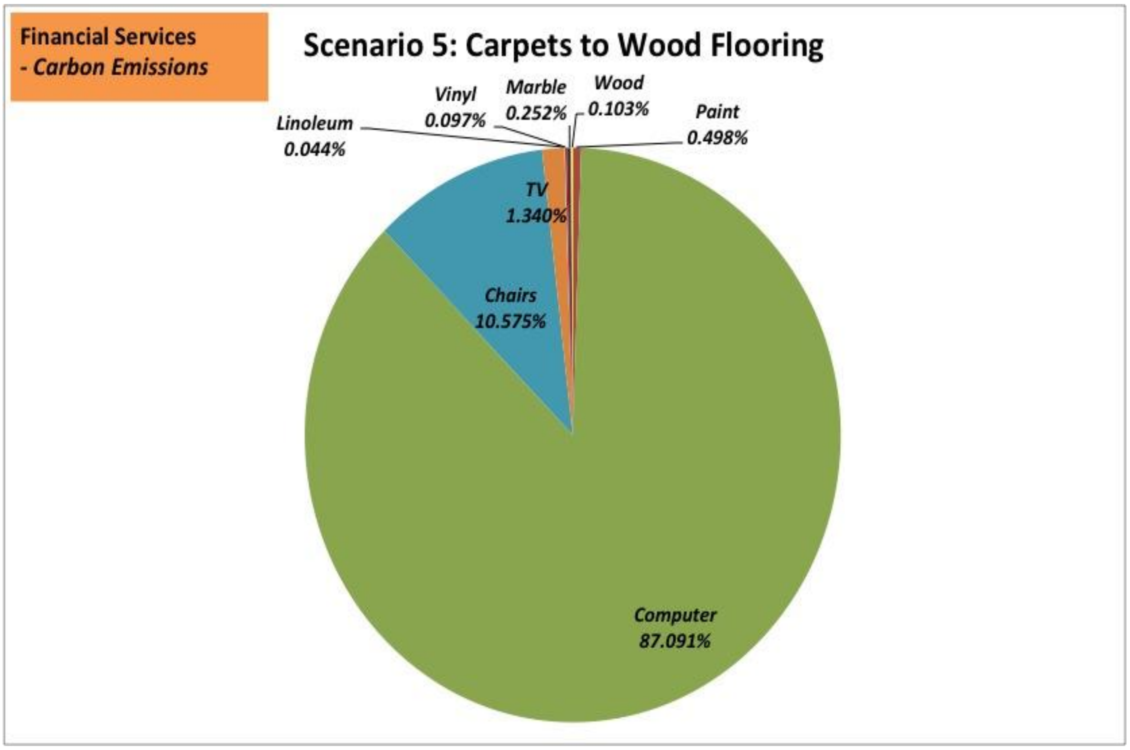
Financial Services
- Carbon Emissions
Scenario 3: Minimum Values
Vinyl 0.468%
Marble 1.584%
Linoleum 0.075%
Paint 0.382%
Carpet 5.287%
TV 9.618%
Computer 40.354%
Chairs 42.232%

18 (D)



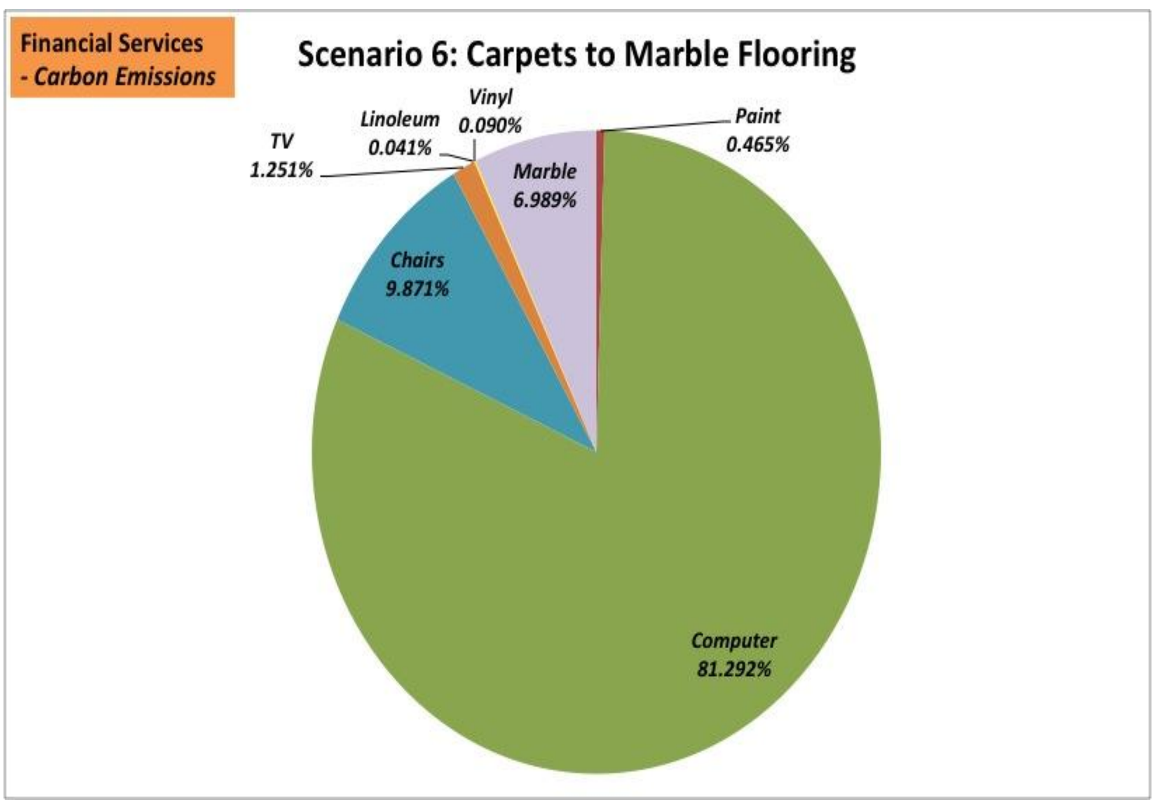
Financial Services
- Carbon Emissions
Scenario 4: 50% Painted Walls to Glass Walls
Linoleum 0.038%
Vinyl 0.083%
Marble 0.216%
TV 1.149%
Carpet 11.038%
Paint 0.214%
Glass 3.531%
Chairs 9.066%
Computer 74.665%

18 (E)



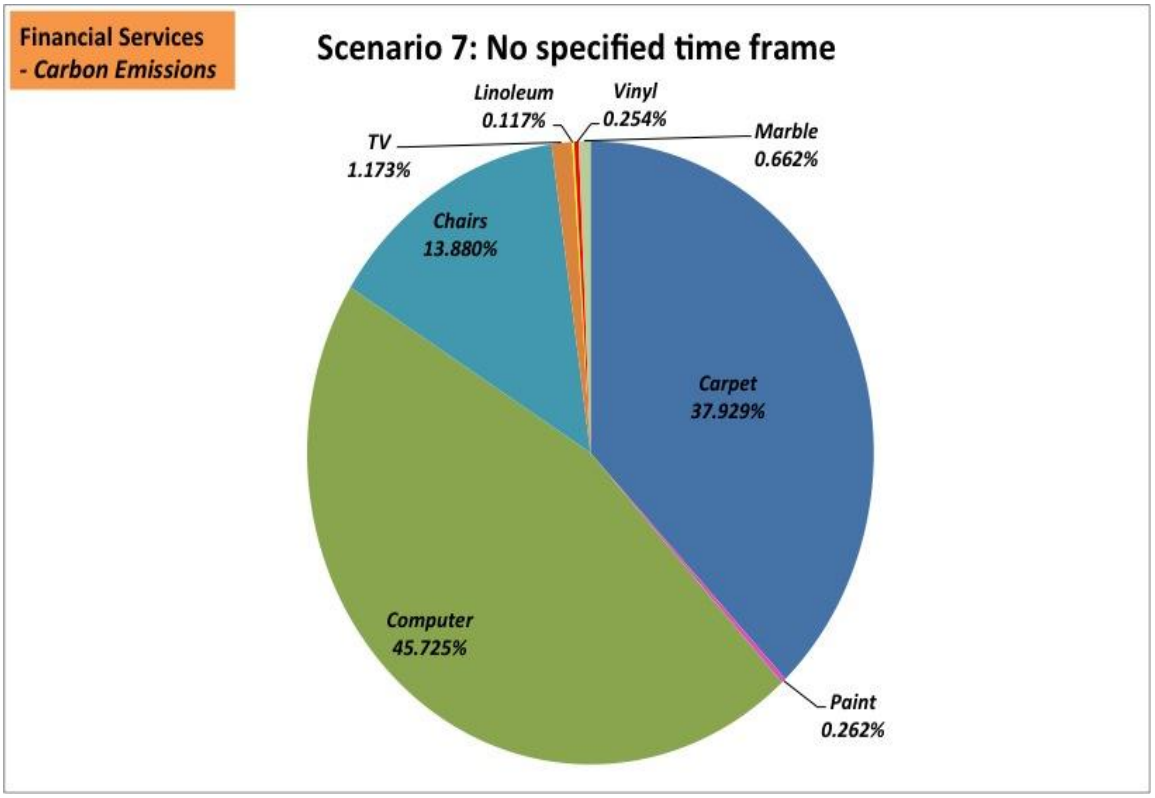
Financial Services
- Carbon Emissions
Scenario 5: Carpets to Wood Flooring
Vinyl
0.097%
Marble
0.252%
Wood
0.103%
Paint
0.498%
Linoleum
0.044%
TV
1.340%
Chairs
10.575%
Computer
87.091%

18 (F)

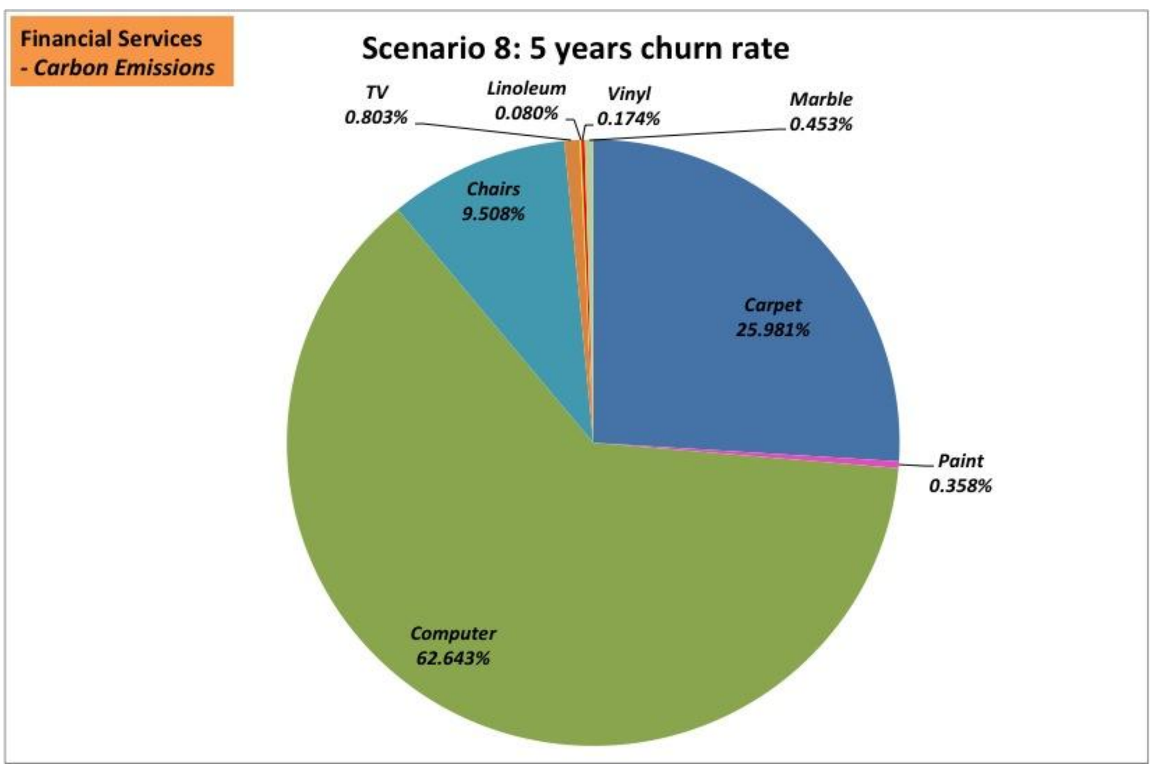


Financial Services
- Carbon Emissions
Scenario 6: Carpets to Marble Flooring
Vinyl
0.090%
Linoleum
0.041%
TV
1.251%
Paint
0.465%
Marble
6.989%
Chairs
9.871%
Computer
81.292%

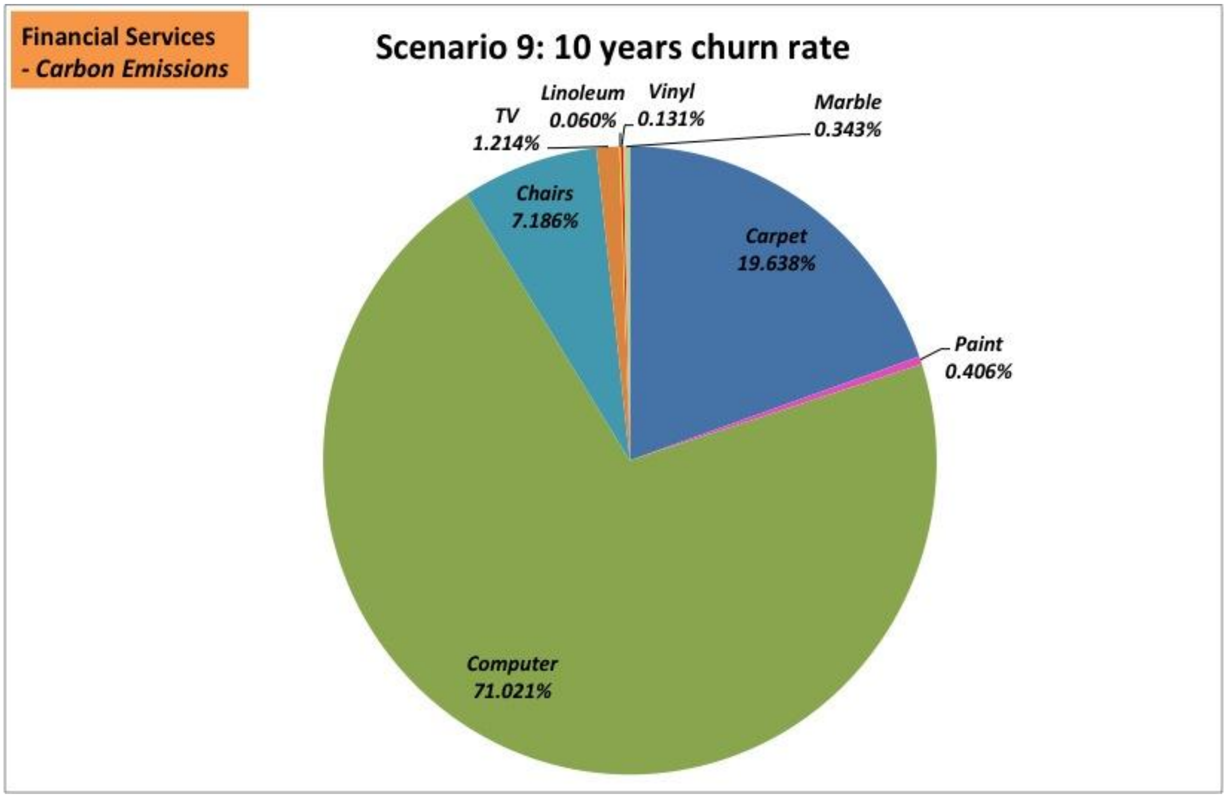
18 (G)


Financial Services
- Carbon Emissions
Scenario 7: No specified time frame
Linoleum
0.117%
Vinyl
0.254%
TV
1.173%
Marble
0.662%
Chairs
13.880%
Carpet
37.929%
Computer
45.725%
Paint
0.262%

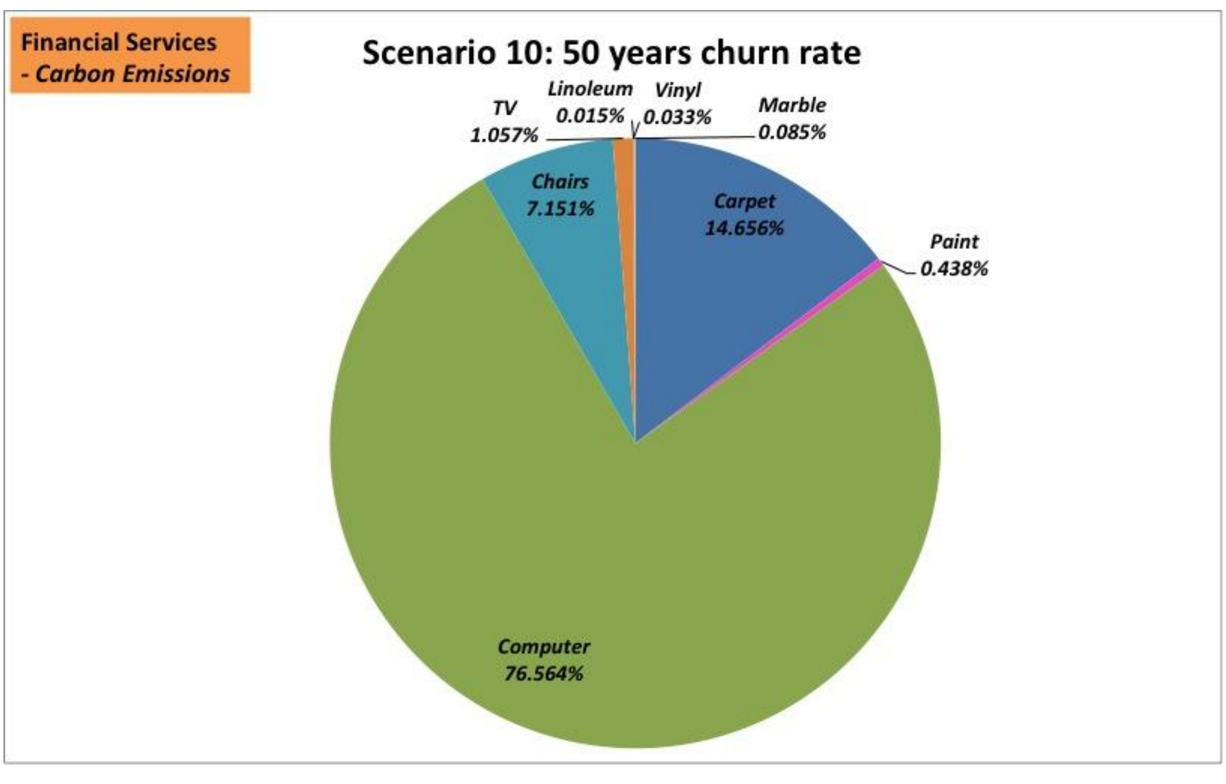
18 (H)


Financial Services
- Carbon Emissions
Scenario 8: 5 years churn rate
TV
0.803%
Linoleum
0.080%
Vinyl
0.174%
Marble
0.453%
Chairs
9.508%
Carpet
25.981%
Paint
0.358%
Computer
62.643%

18 (I)


Financial Services
- Carbon Emissions
Scenario 9: 10 years churn rate
Linoleum 0.060%
Vinyl 0.131%
Marble 0.343%
TV 1.214%
Chairs 7.186%
Carpet 19.638%
Paint 0.406%
Computer 71.021%

18 (J)


Financial Services
- Carbon Emissions
Scenario 10: 50 years churn rate
Linoleum 0.015%
Vinyl 0.033%
Marble 0.085%
TV 1.057%
Chairs 7.151%
Carpet 14.656%
Paint 0.438%
Computer 76.564%

18 (K)

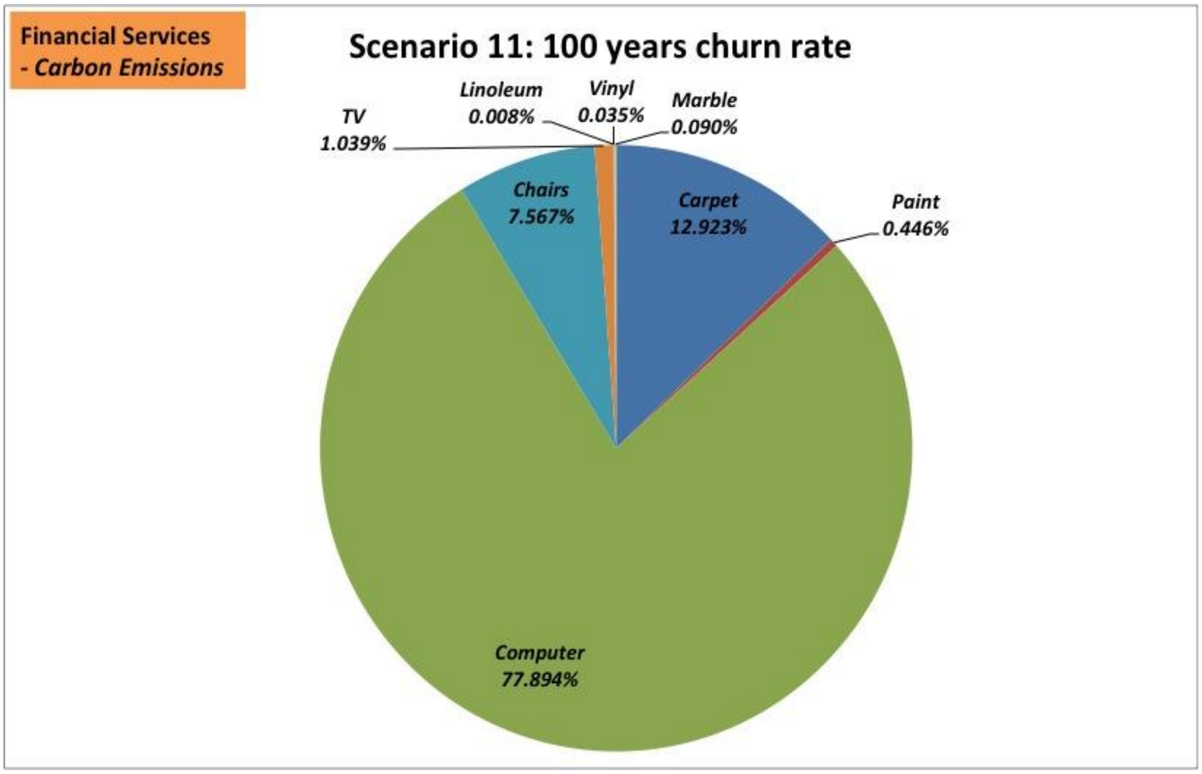
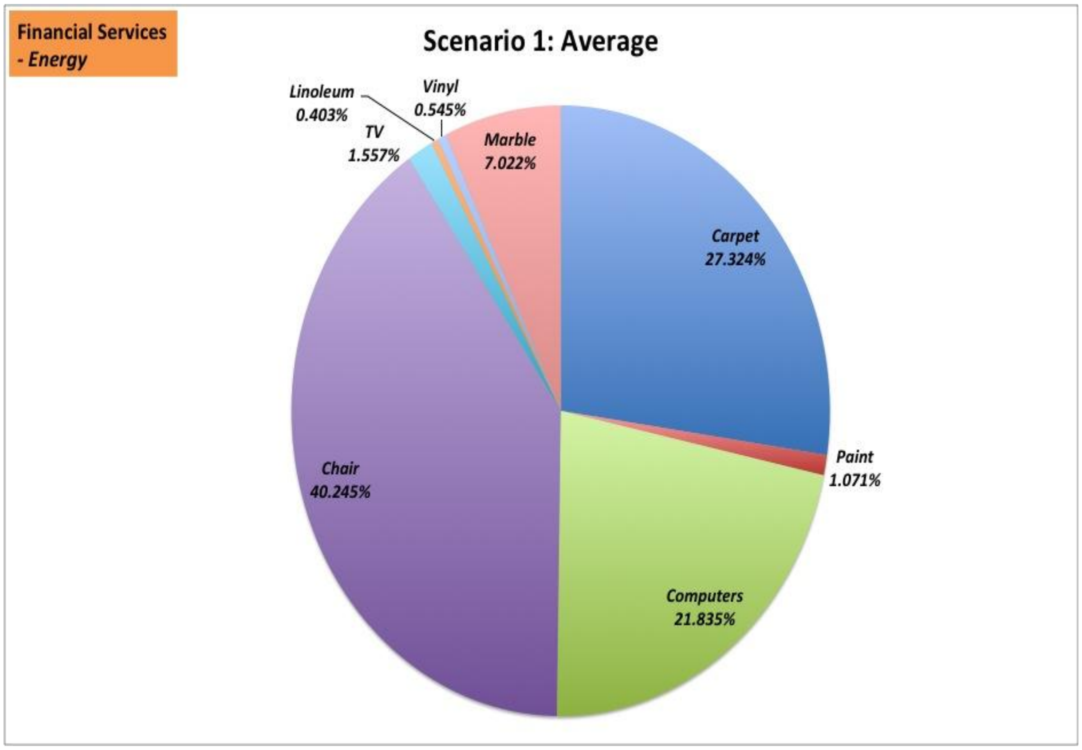
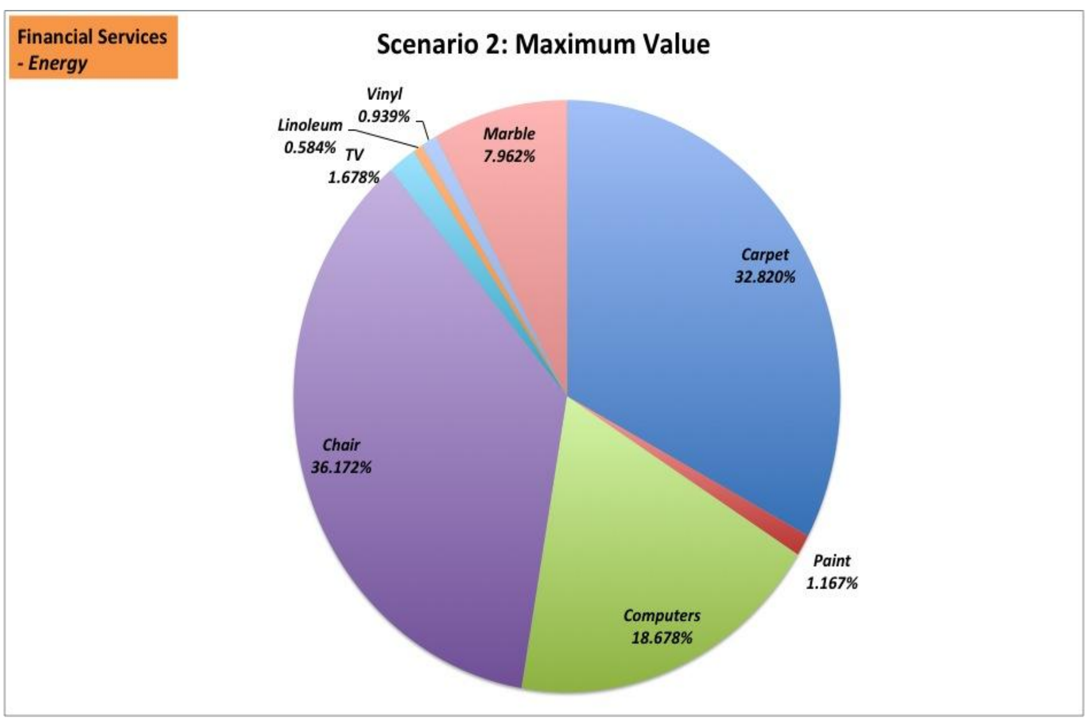


Figure 18. These pie charts are CO2 data for the financial scenarios. Each pie chart shows the percent contribution of each component for each scenario.

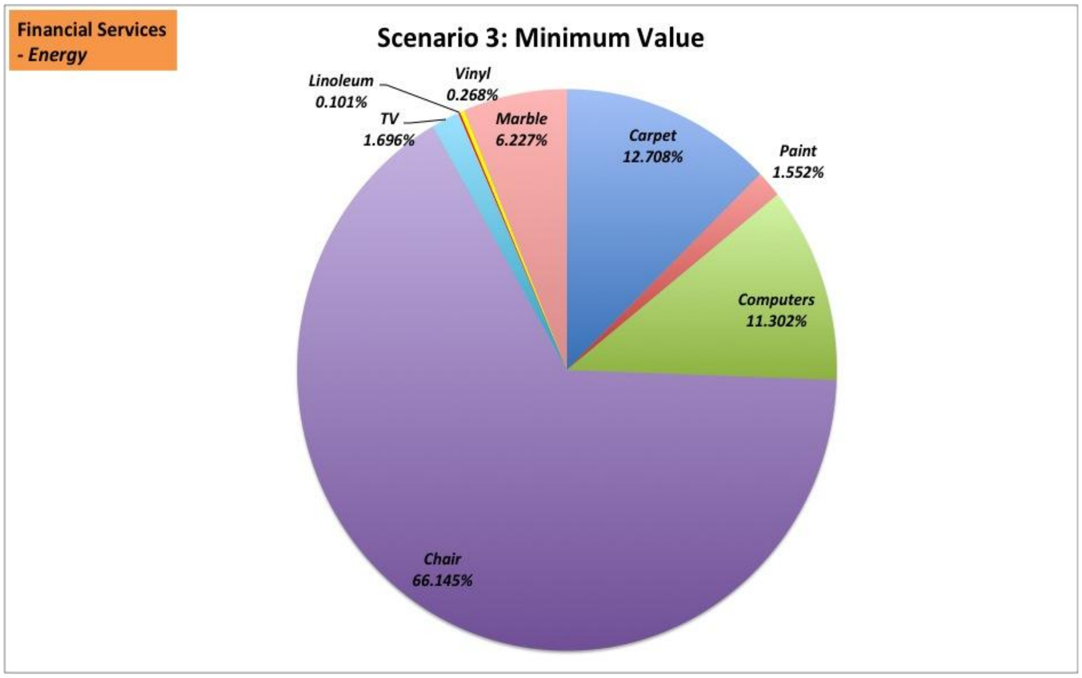
19 (A)


Financial Services
- Energy
Scenario 1: Average
Linoleum
0.403%
Vinyl
0.545%
TV
1.557%
Marble
7.022%
Carpet
27.324%
Paint
1.071%
Chair
40.245%
Computers
21.835%

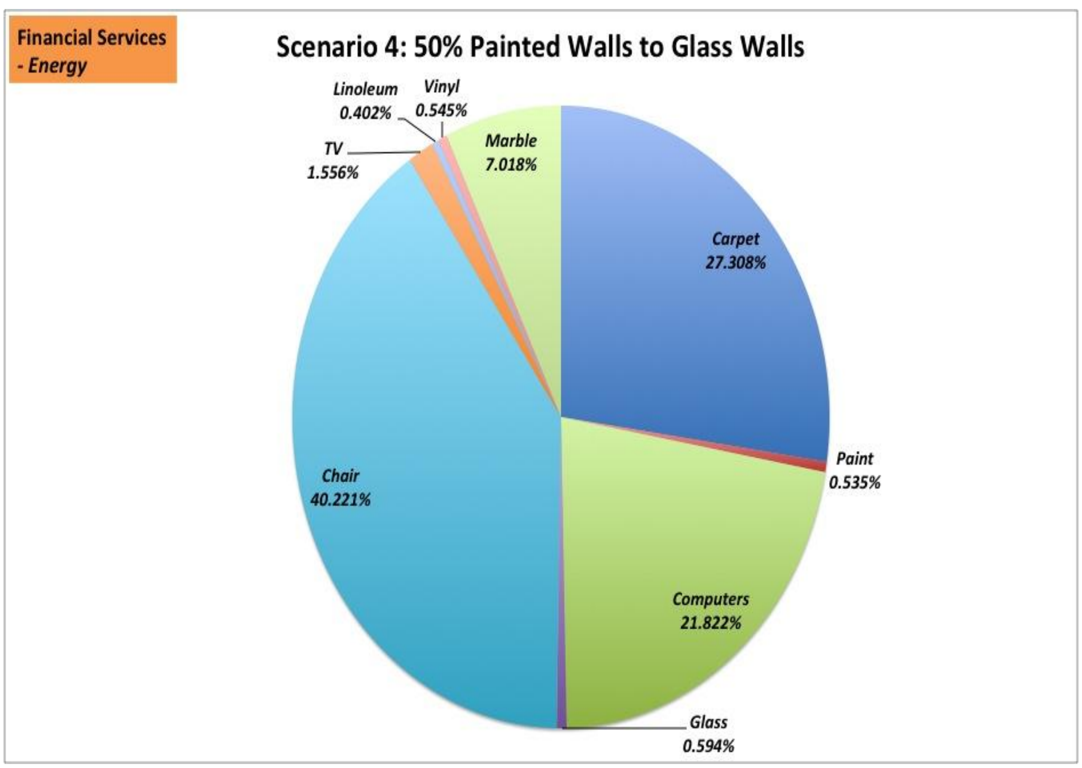
19 (B)


Financial Services
- Energy
Scenario 2: Maximum Value
Vinyl
0.939%
Linoleum
0.584%
TV
1.678%
Marble
7.962%
Carpet
32.820%
Chair
36.172%
Paint
1.167%
Computers
18.678%

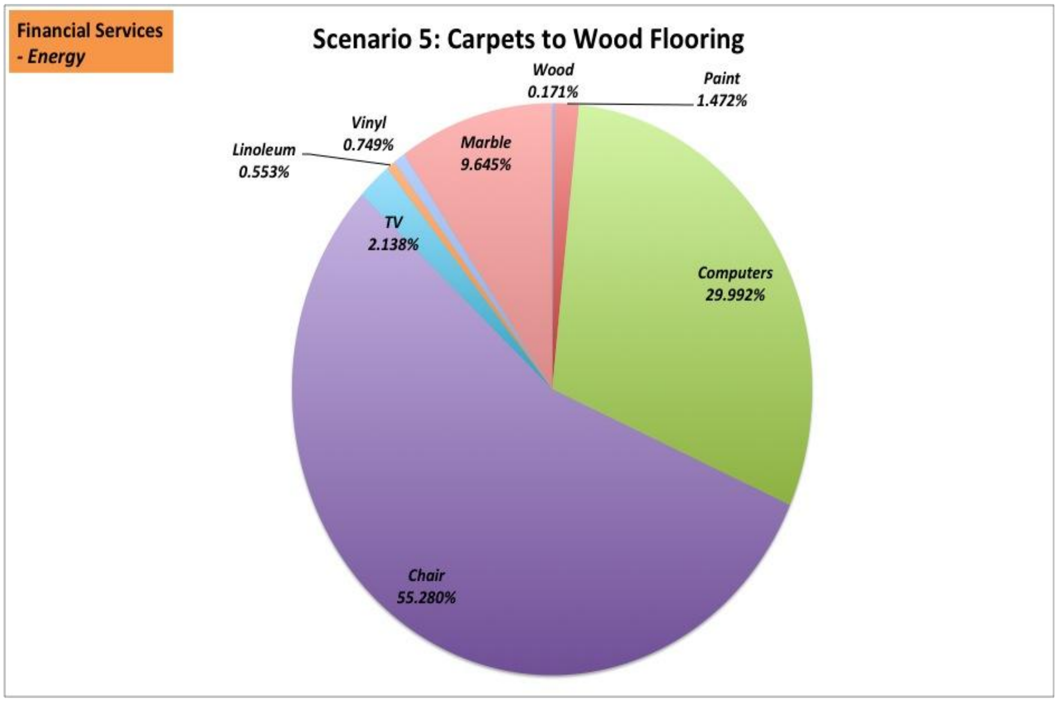
19 (C)


Financial Services
- Energy
Scenario 3: Minimum Value
Linoleum
0.101%
Vinyl
0.268%
TV
1.696%
Marble
6.227%
Carpet
12.708%
Paint
1.552%
Computers
11.302%
Chair
66.145%

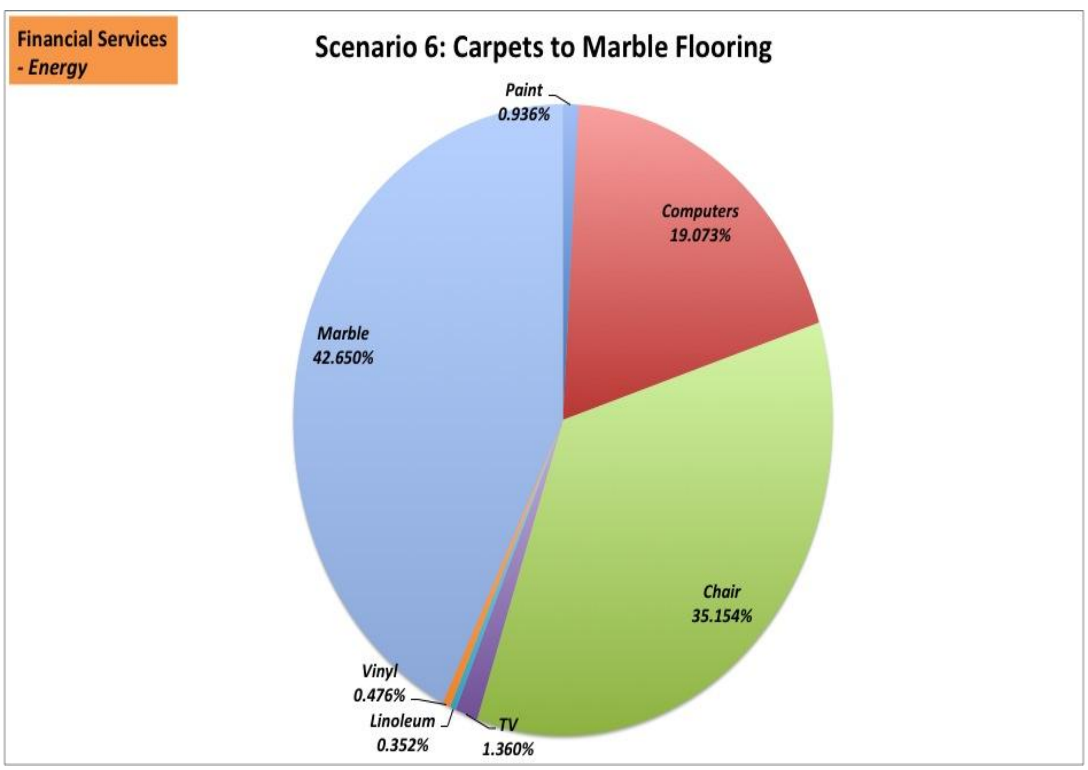
19 (D)


Financial Services
- Energy
Scenario 4: 50% Painted Walls to Glass Walls
Linoleum
0.402%
Vinyl
0.545%
TV
1.556%
Marble
7.018%
Carpet
27.308%
Paint
0.535%
Chair
40.221%
Computers
21.822%
Glass
0.594%

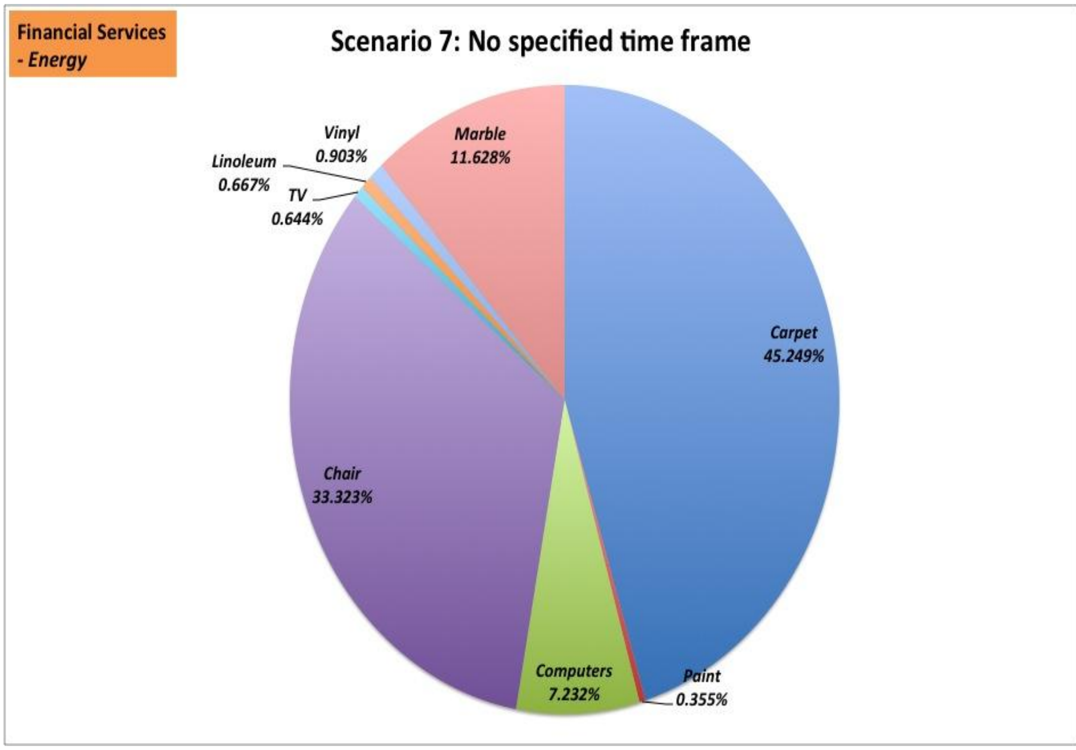
19 (E)


Financial Services
- Energy
Scenario 5: Carpets to Wood Flooring
Wood
0.171%
Paint
1.472%
Vinyl
0.749%
Linoleum
0.553%
Marble
9.645%
TV
2.138%
Computers
29.992%
Chair
55.280%

19 (F)

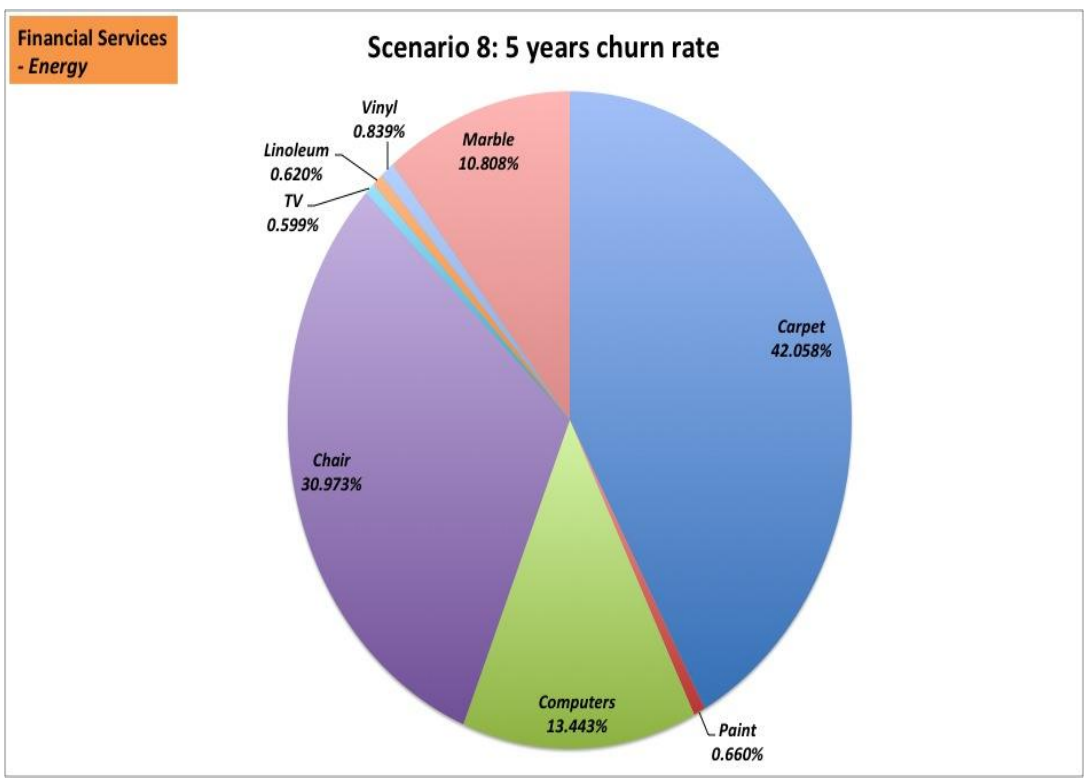

Financial Services
- Energy
Scenario 6: Carpets to Marble Flooring
Paint
0.936%
Computers
19.073%
Marble
42.650%
Chair
35.154%
Vinyl
0.476%
Linoleum
0.352%
TV
1.360%

19 (G)



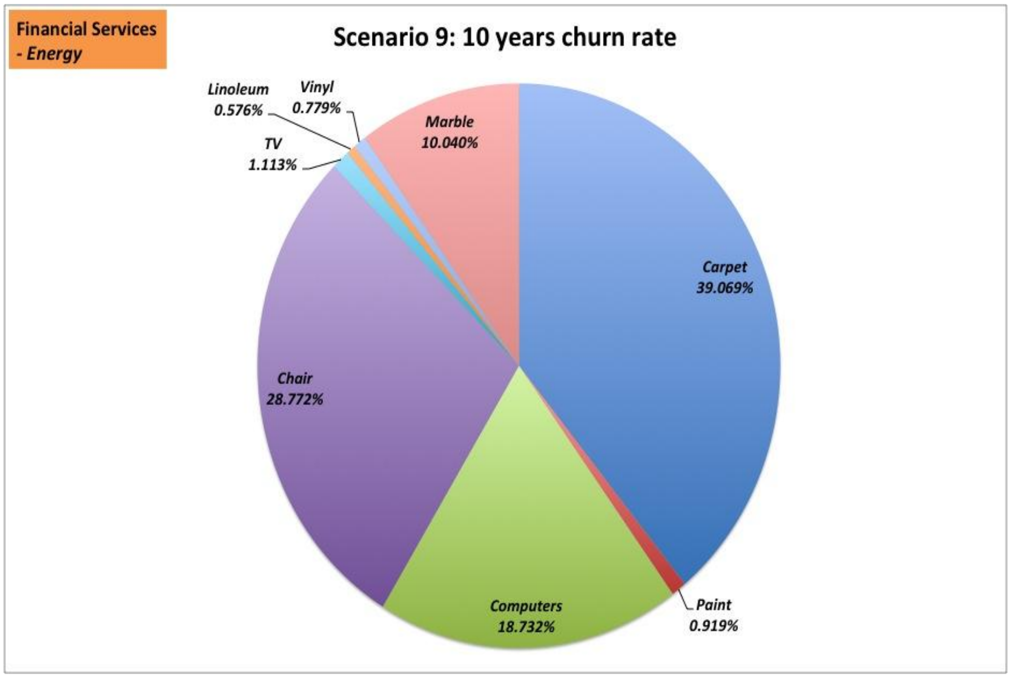
Financial Services
- Energy
Scenario 7: No specified time frame
Vinyl
0.903%
Marble
11.628%
Linoleum
0.667%
TV
0.644%
Carpet
45.249%
Chair
33.323%
Computers
7.232%
Paint
0.355%

19 (H)

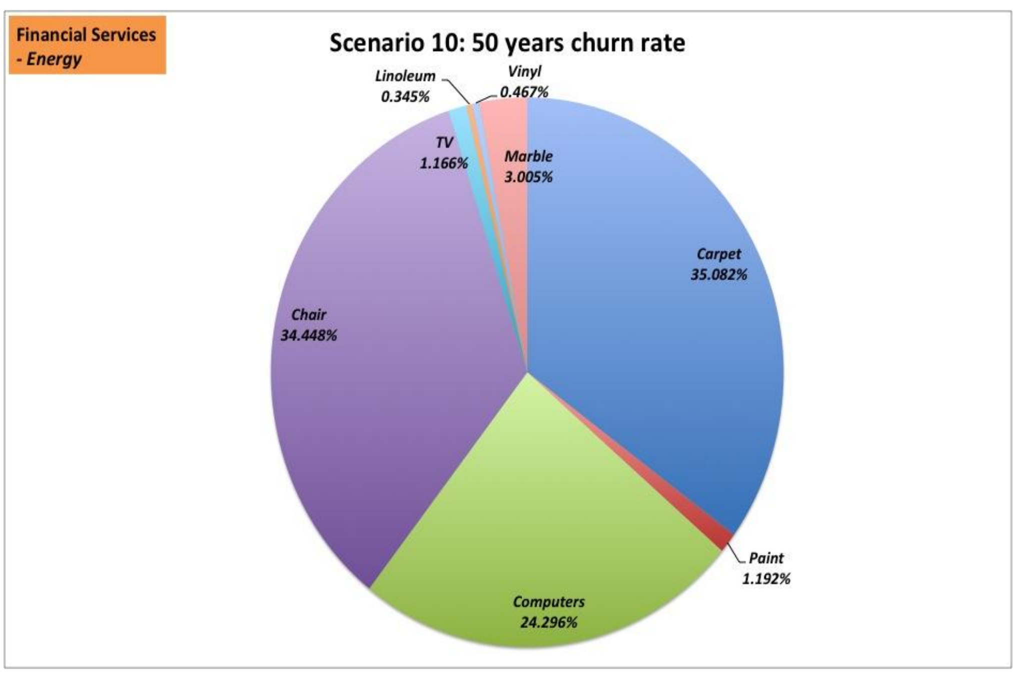


Financial Services
- Energy
Scenario 8: 5 years churn rate
Vinyl
0.839%
Marble
10.808%
Linoleum
0.620%
TV
0.599%
Carpet
42.058%
Chair
30.973%
Computers
13.443%
Paint
0.660%

19 (I)


Financial Services
- Energy
Scenario 9: 10 years churn rate
Linoleum
0.576%
Vinyl
0.779%
TV
1.113%
Marble
10.040%
Carpet
39.069%
Chair
28.772%
Computers
18.732%
Paint
0.919%

19 (J)


Financial Services
- Energy
Scenario 10: 50 years churn rate
Linoleum
0.345%
Vinyl
0.467%
TV
1.166%
Marble
3.005%
Carpet
35.082%
Chair
34.448%
Paint
1.192%
Computers
24.296%

19 (K)

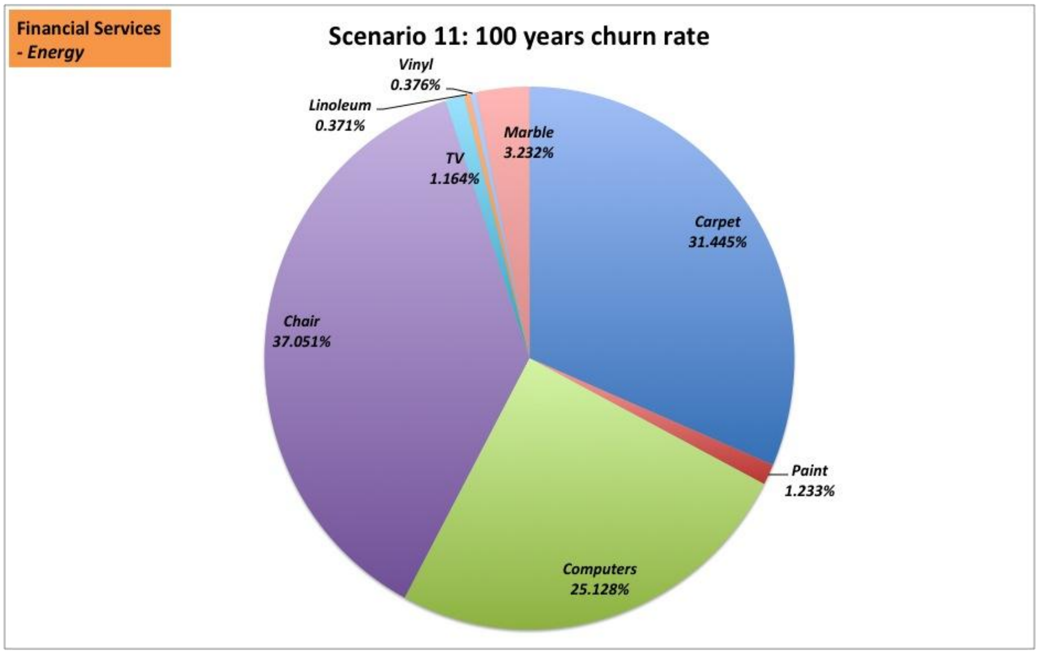
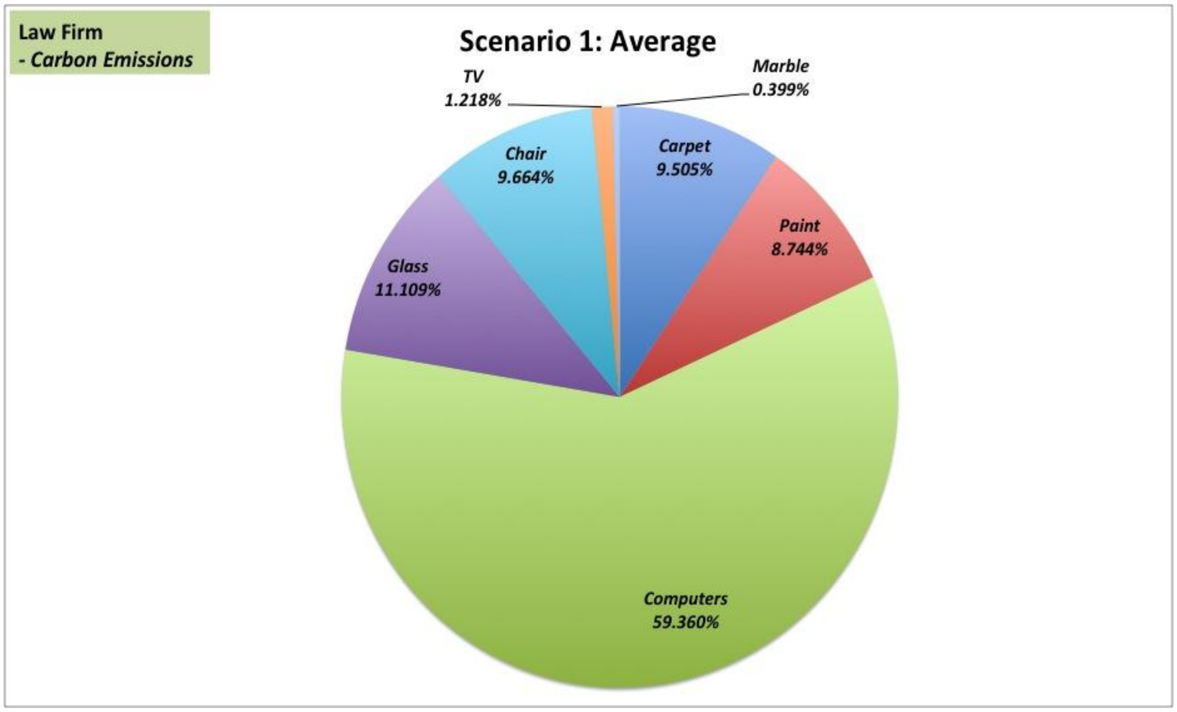
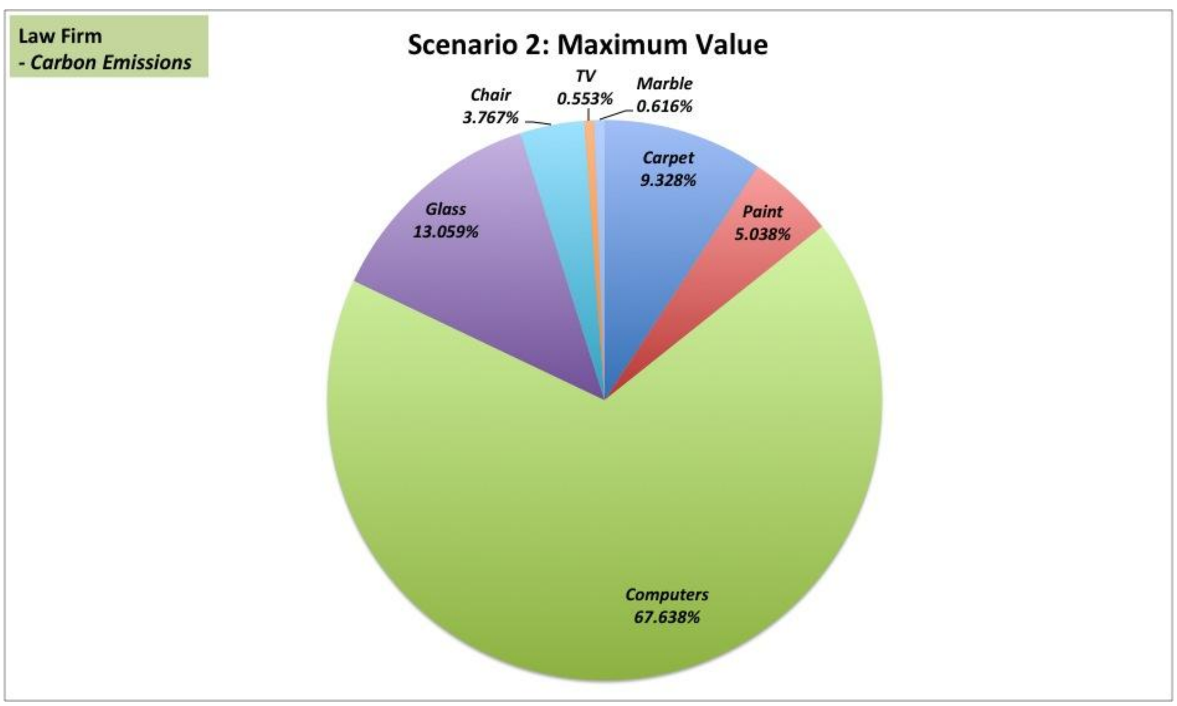


Figure 19. These pie charts are energy data for the financial scenarios. Each pie chart shows the percent contribution of each component for each scenario.

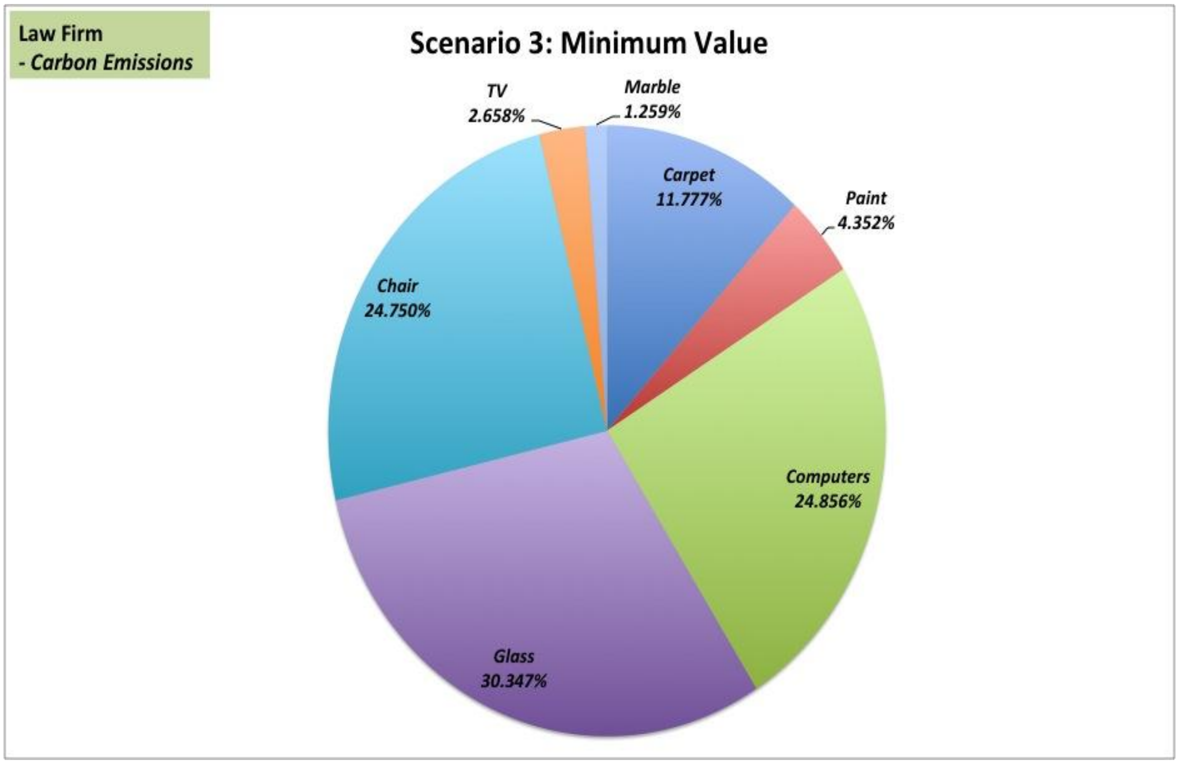
20 (A)


Law Firm
- Carbon Emissions
Scenario 1: Average
TV
1.218%
Marble
0.399%
Chair
9.664%
Carpet
9.505%
Paint
8.744%
Glass
11.109%
Computers
59.360%

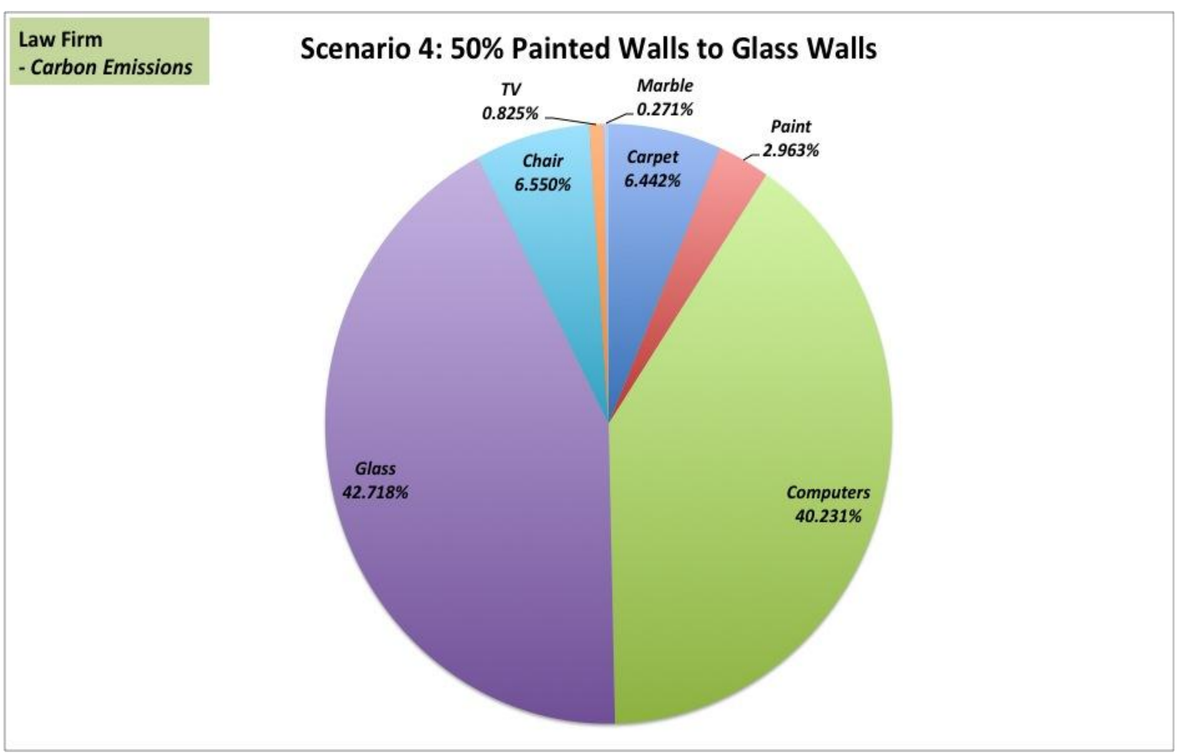
20 (B)


Law Firm
- Carbon Emissions
Scenario 2: Maximum Value
Chair
3.767%
TV
0.553%
Marble
0.616%
Carpet
9.328%
Paint
5.038%
Glass
13.059%
Computers
67.638%

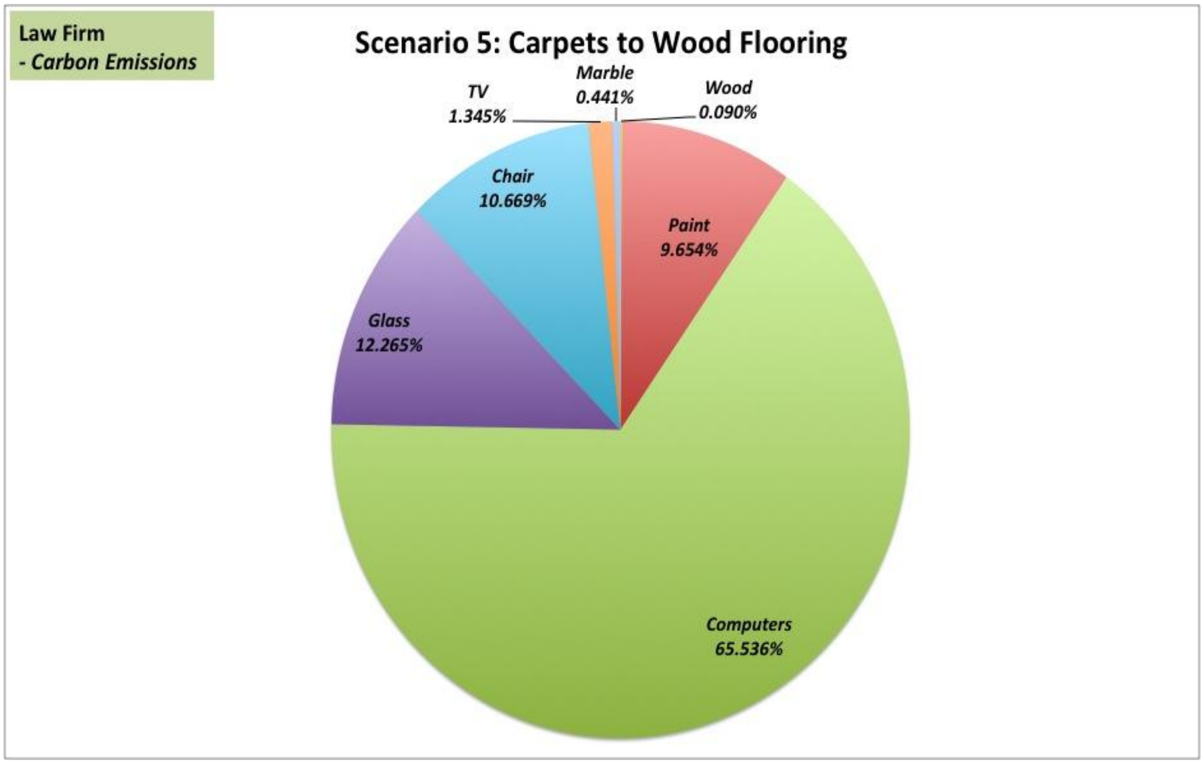
20 (C)


Law Firm
- Carbon Emissions
Scenario 3: Minimum Value
TV 2.658%
Marble 1.259%
Carpet 11.777%
Paint 4.352%
Chair 24.750%
Computers 24.856%
Glass 30.347%

20 (D)

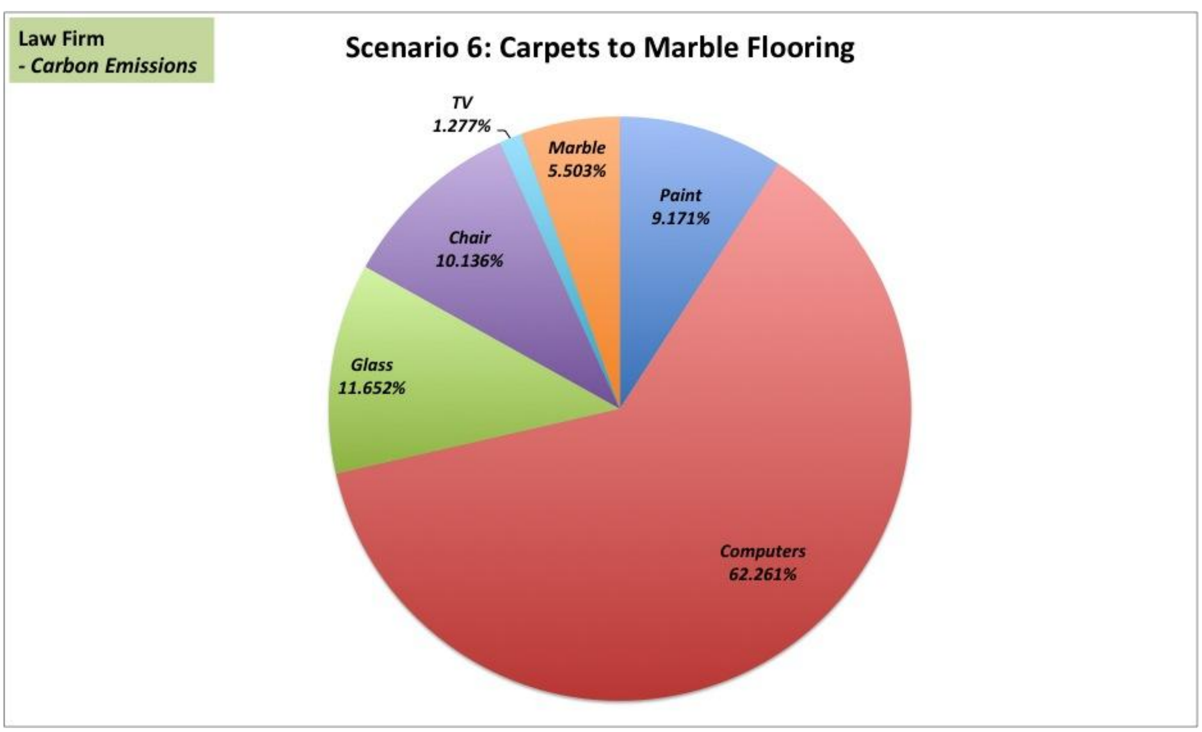

Law Firm
- Carbon Emissions
Scenario 4: 50% Painted Walls to Glass Walls
TV 0.825%
Marble 0.271%
Paint 2.963%
Chair 6.550%
Carpet 6.442%
Glass 42.718%
Computers 40.231%

20 (E)



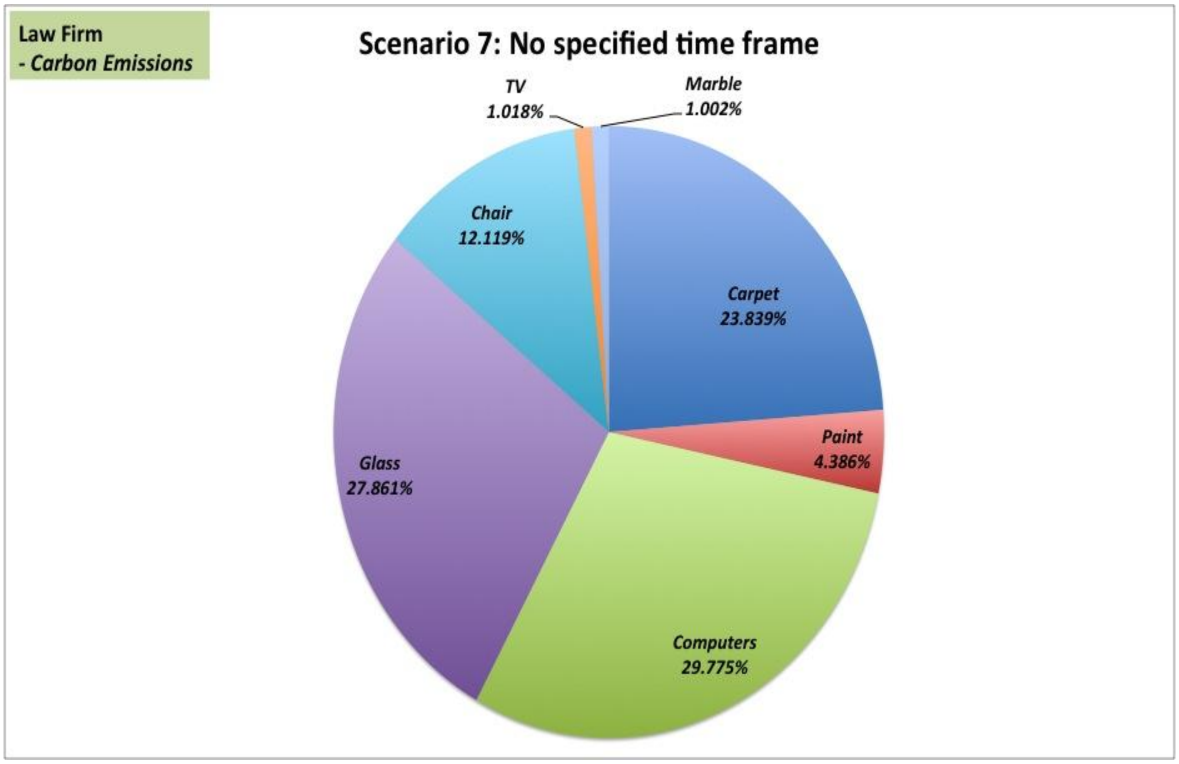
Law Firm
- Carbon Emissions
Scenario 5: Carpets to Wood Flooring
TV
1.345%
Marble
0.441%
Wood
0.090%
Chair
10.669%
Paint
9.654%
Glass
12.265%
Computers
65.536%

20 (F)

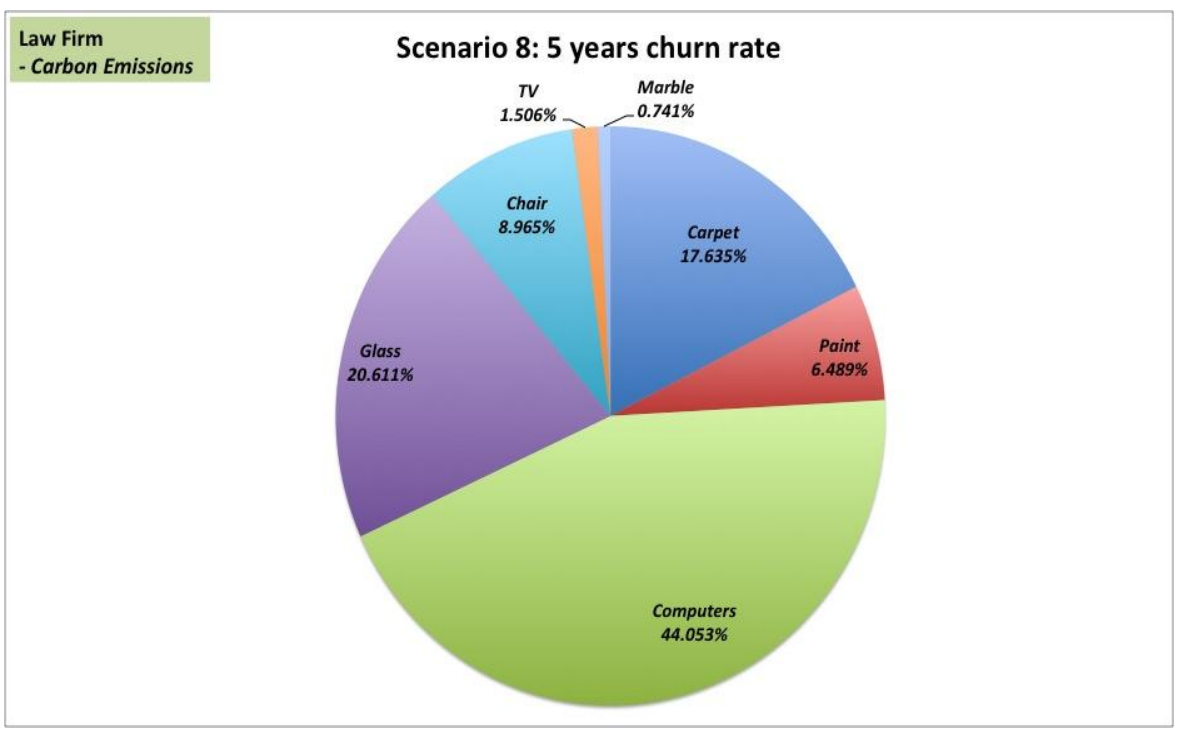


Law Firm
- Carbon Emissions
Scenario 6: Carpets to Marble Flooring
TV
1.277%
Marble
5.503%
Paint
9.171%
Chair
10.136%
Glass
11.652%
Computers
62.261%

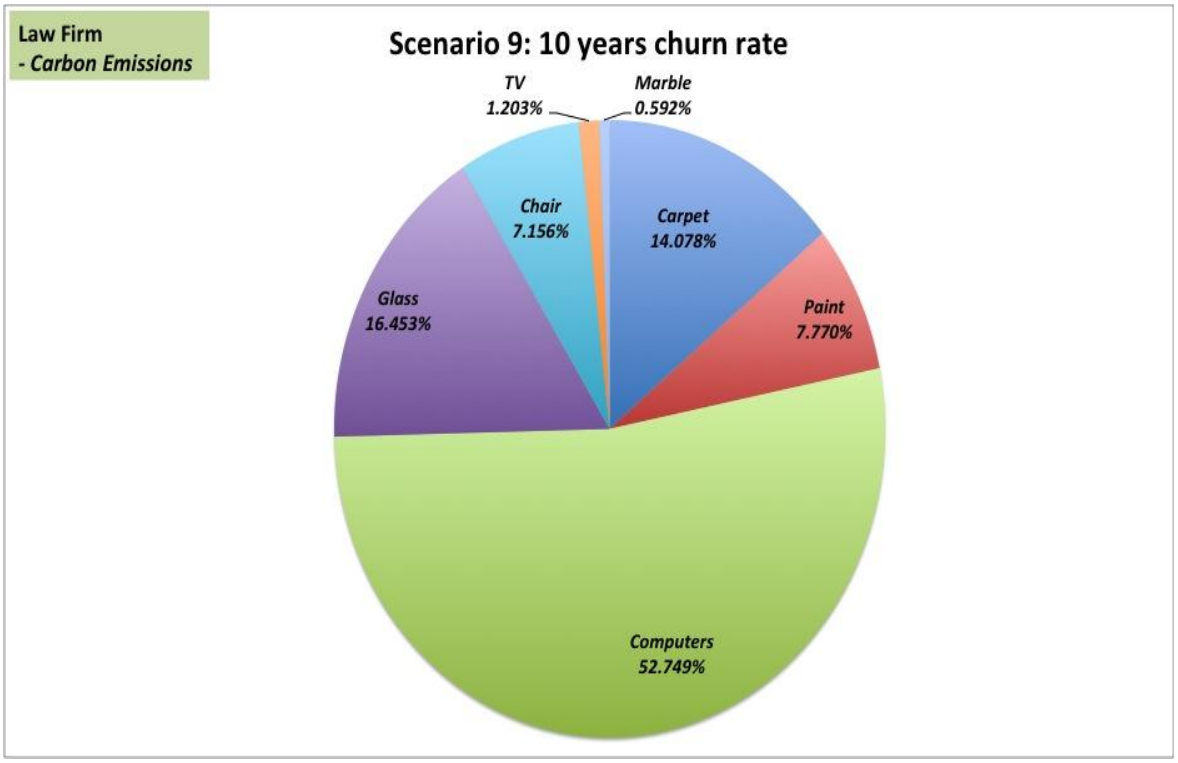
20 (G)


Law Firm
- Carbon Emissions
Scenario 7: No specified time frame
TV
1.018%
Marble
1.002%
Chair
12.119%
Carpet
23.839%
Paint
4.386%
Glass
27.861%
Computers
29.775%

20 (H)

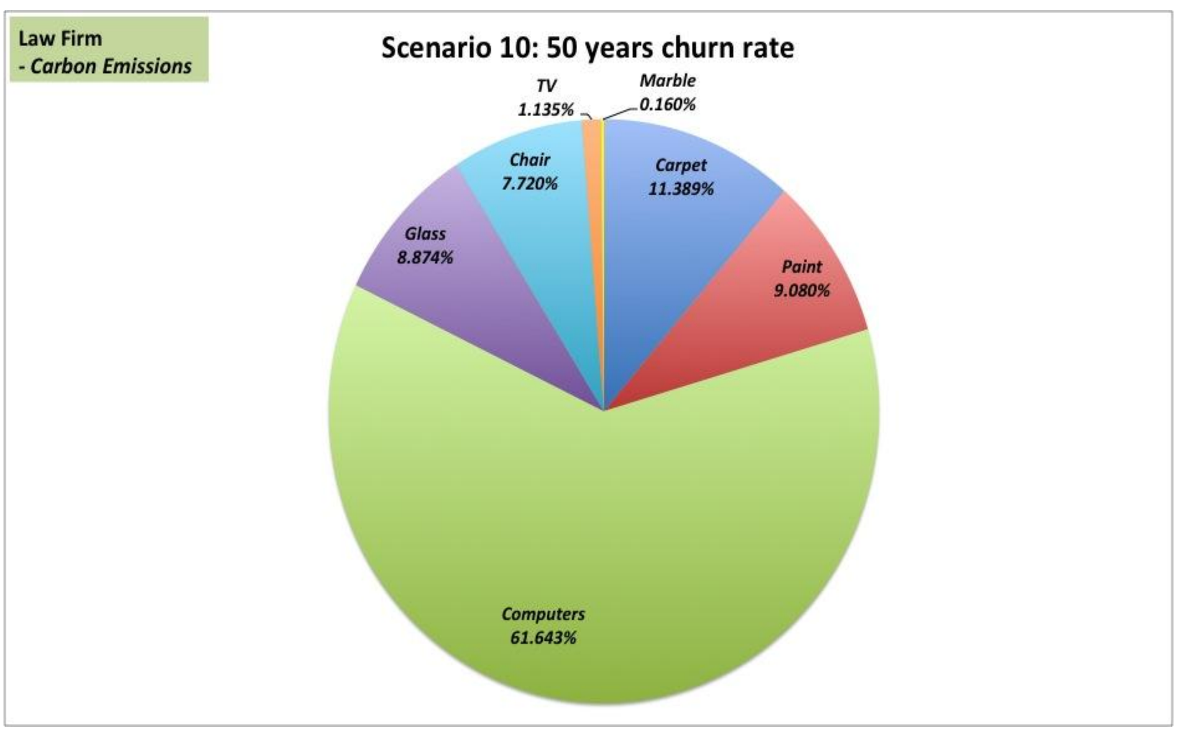

Law Firm
- Carbon Emissions
Scenario 8: 5 years churn rate
TV
1.506%
Marble
0.741%
Chair
8.965%
Carpet
17.635%
Paint
6.489%
Glass
20.611%
Computers
44.053%

20 (I)



Law Firm
- Carbon Emissions
Scenario 9: 10 years churn rate
TV
1.203%
Marble
0.592%
Chair
7.156%
Carpet
14.078%
Glass
16.453%
Paint
7.770%
Computers
52.749%

20 (J)



Law Firm
- Carbon Emissions
Scenario 10: 50 years churn rate
TV
1.135%
Marble
0.160%
Chair
7.720%
Carpet
11.389%
Glass
8.874%
Paint
9.080%
Computers
61.643%

20 (K)

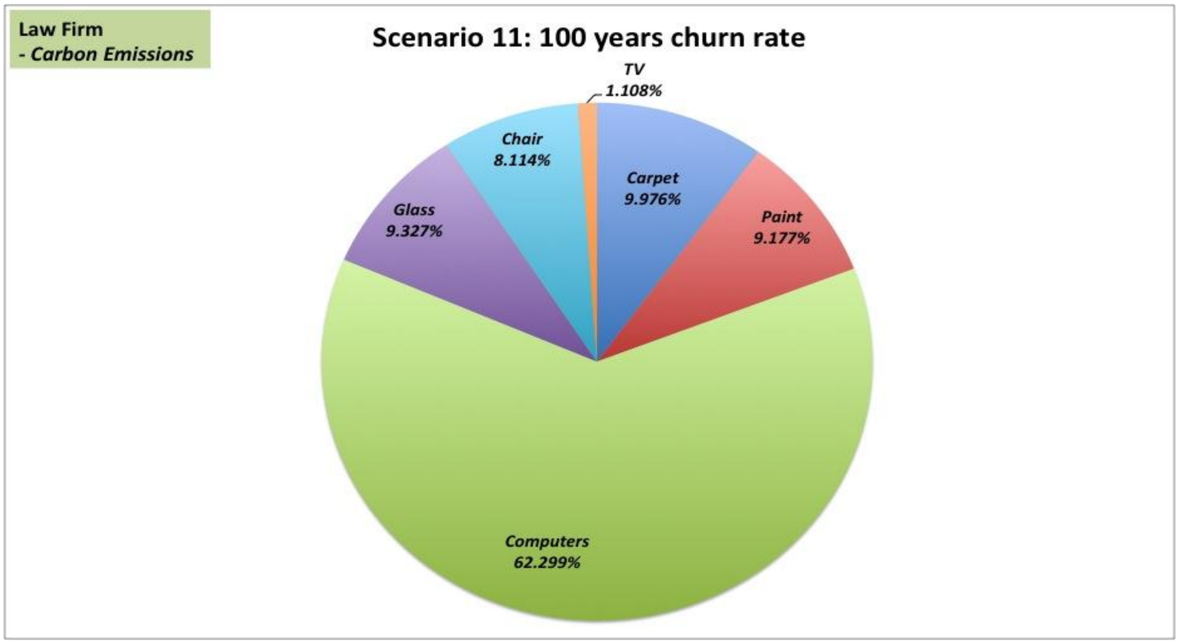
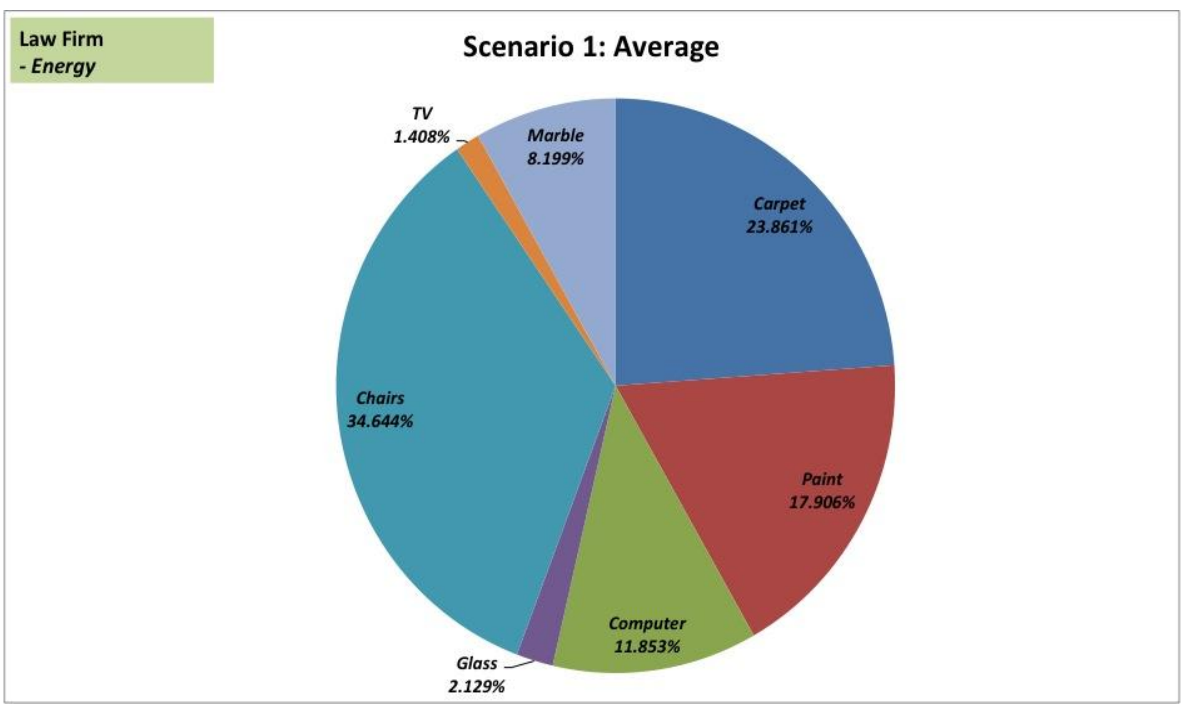
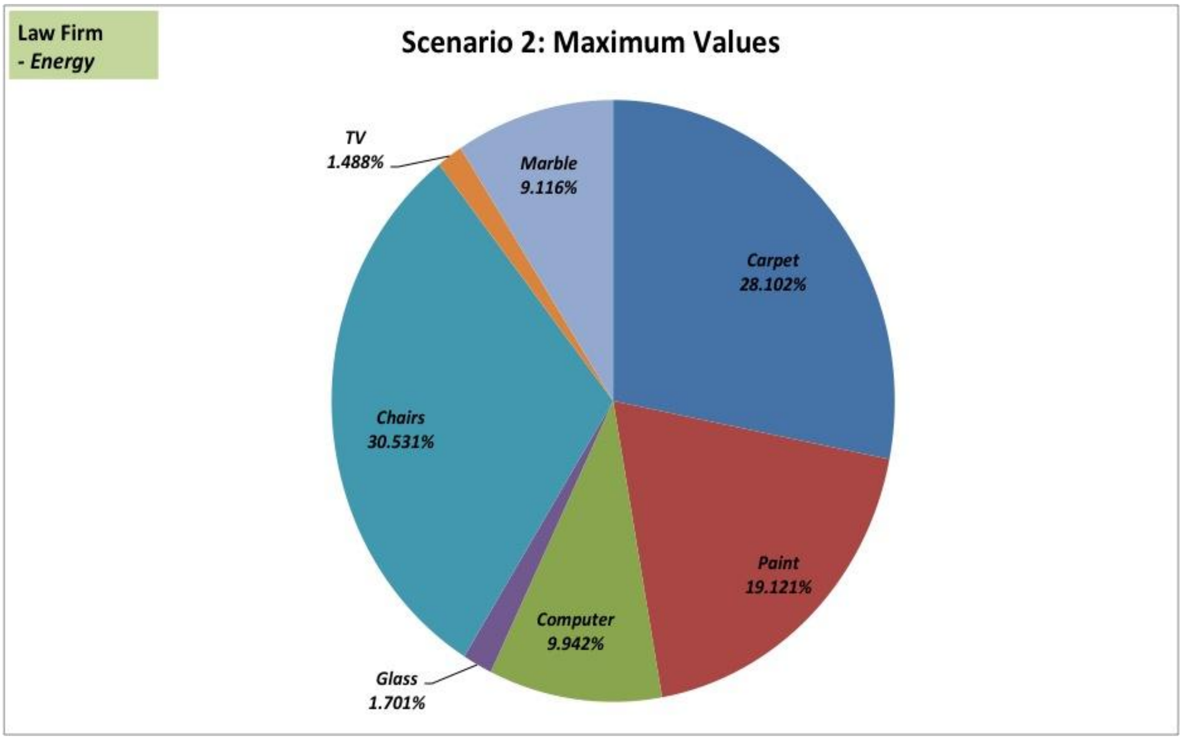


Figure 20. These pie charts are CO2 data for the law firm scenarios. Each pie chart shows the percent contribution of each component for each scenario.

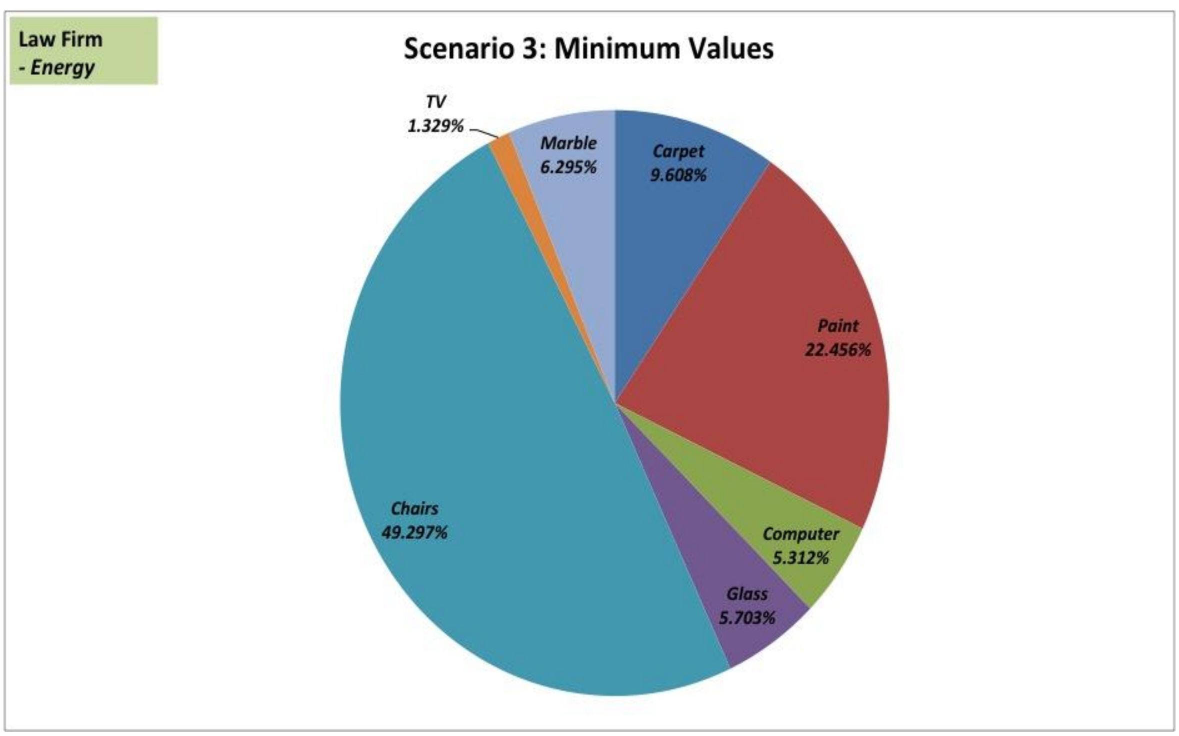
21 (A)



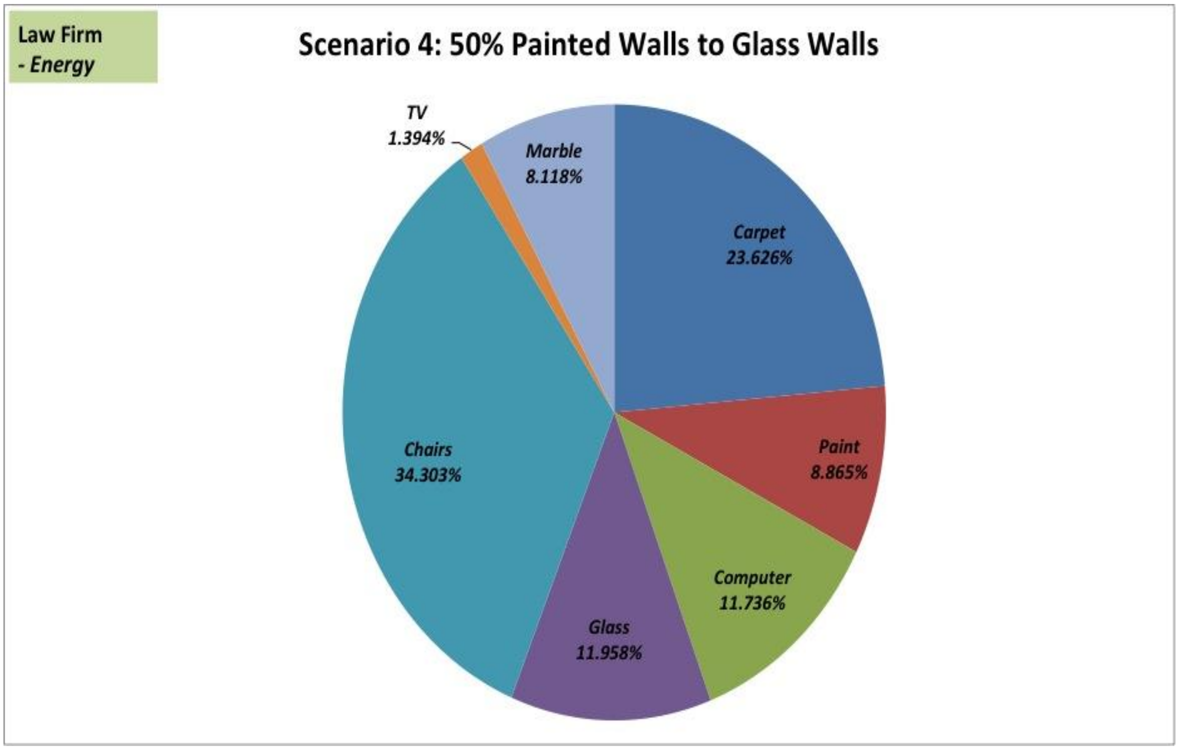
21 (B)


Law Firm
- Energy
Scenario 2: Maximum Values
TV
1.488%
Marble
9.116%
Carpet
28.102%
Chairs
30.531%
Paint
19.121%
Computer
9.942%
Glass
1.701%

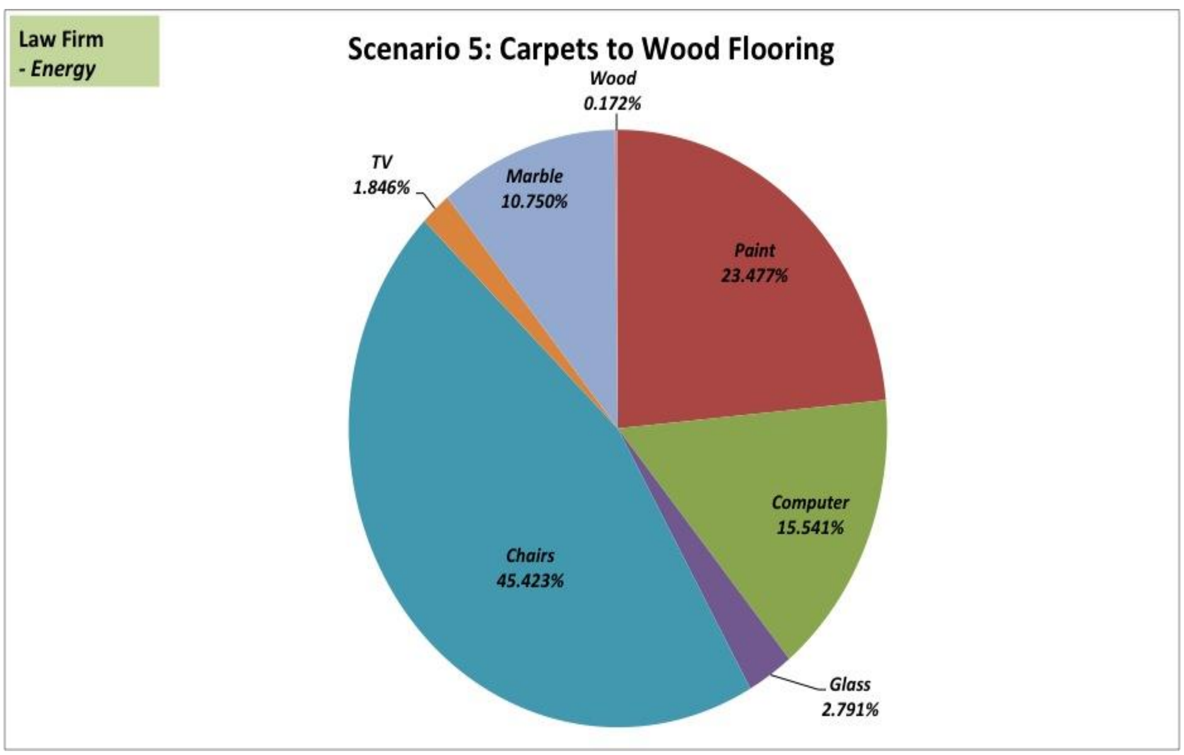
21 (C)


Law Firm
- Energy
Scenario 3: Minimum Values
TV
1.329%
Marble
6.295%
Carpet
9.608%
Paint
22.456%
Chairs
49.297%
Computer
5.312%
Glass
5.703%

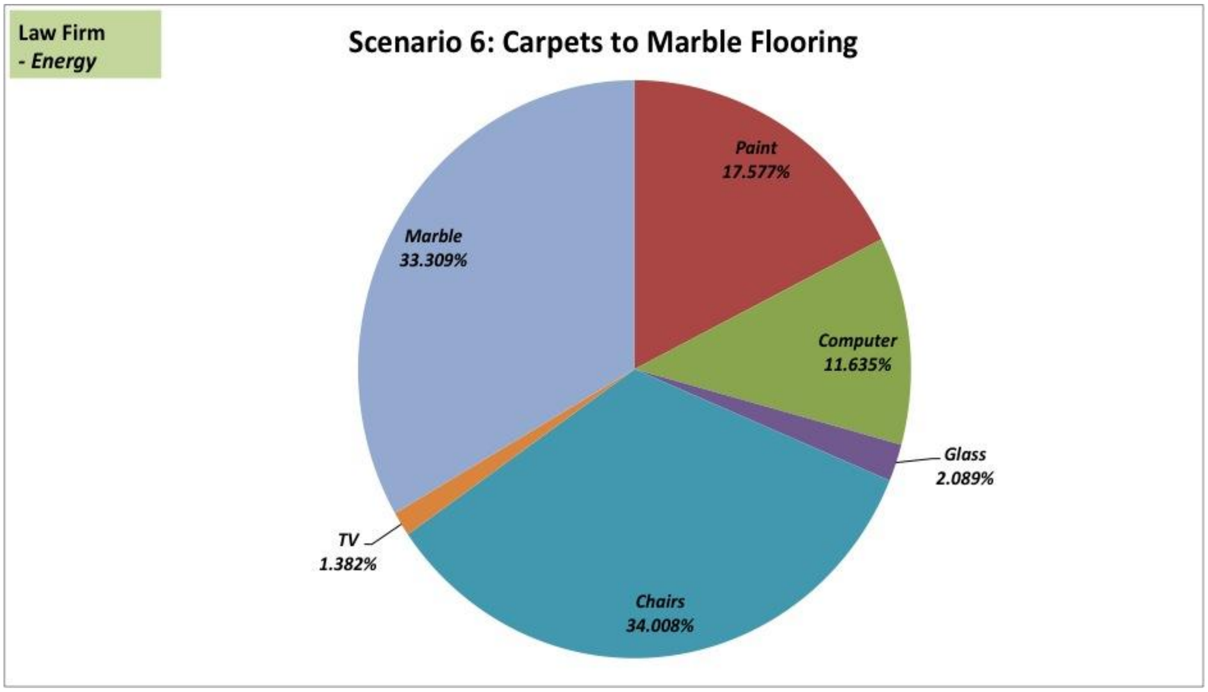
21 (D)


Law Firm
- Energy
Scenario 4: 50% Painted Walls to Glass Walls
TV
1.394%
Marble
8.118%
Carpet
23.626%
Paint
8.865%
Computer
11.736%
Glass
11.958%
Chairs
34.303%

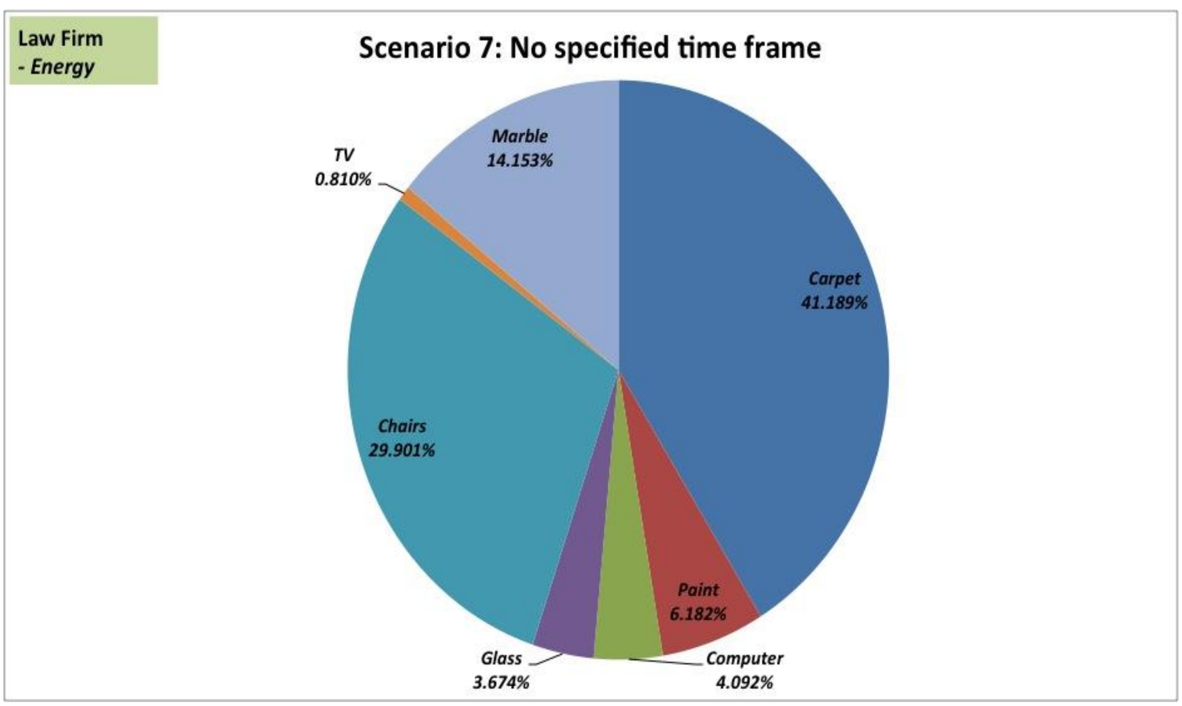
21 (E)


Law Firm
- Energy
Scenario 5: Carpets to Wood Flooring
Wood
0.172%
TV
1.846%
Marble
10.750%
Paint
23.477%
Computer
15.541%
Glass
2.791%
Chairs
45.423%

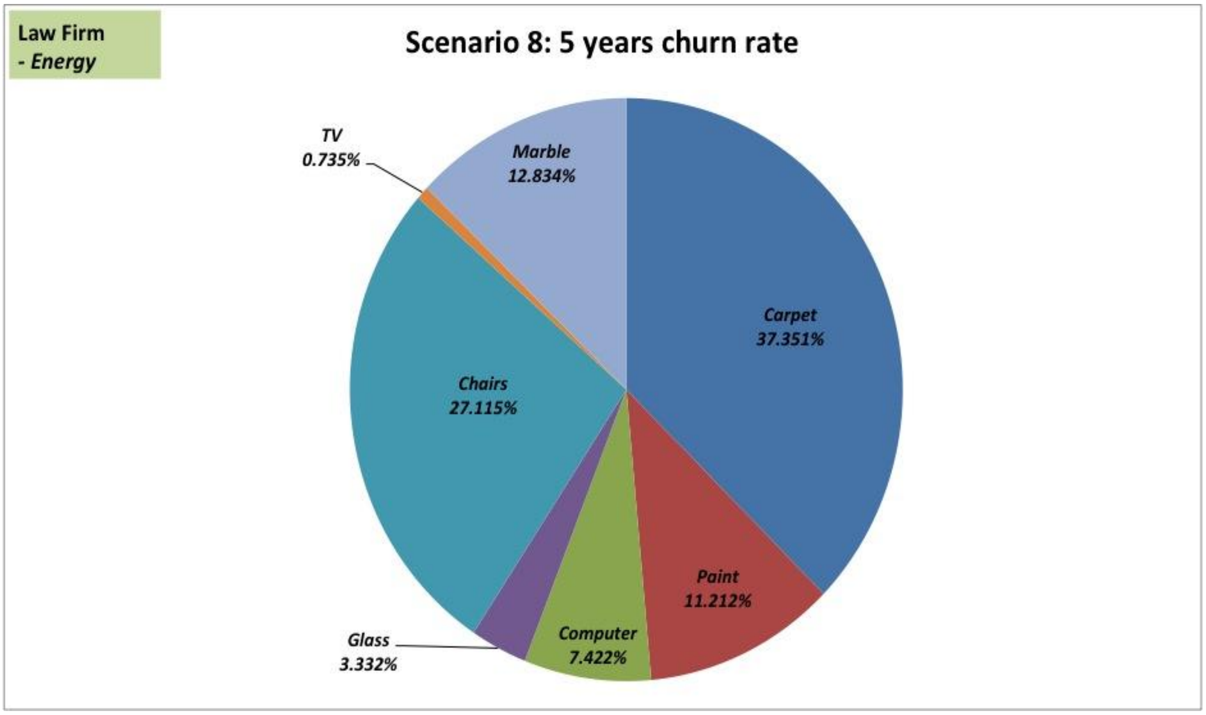
21 (F)


Law Firm
- Energy
Scenario 6: Carpets to Marble Flooring
Paint
17.577%
Computer
11.635%
Glass
2.089%
Chairs
34.008%
TV
1.382%
Marble
33.309%

21 (G)

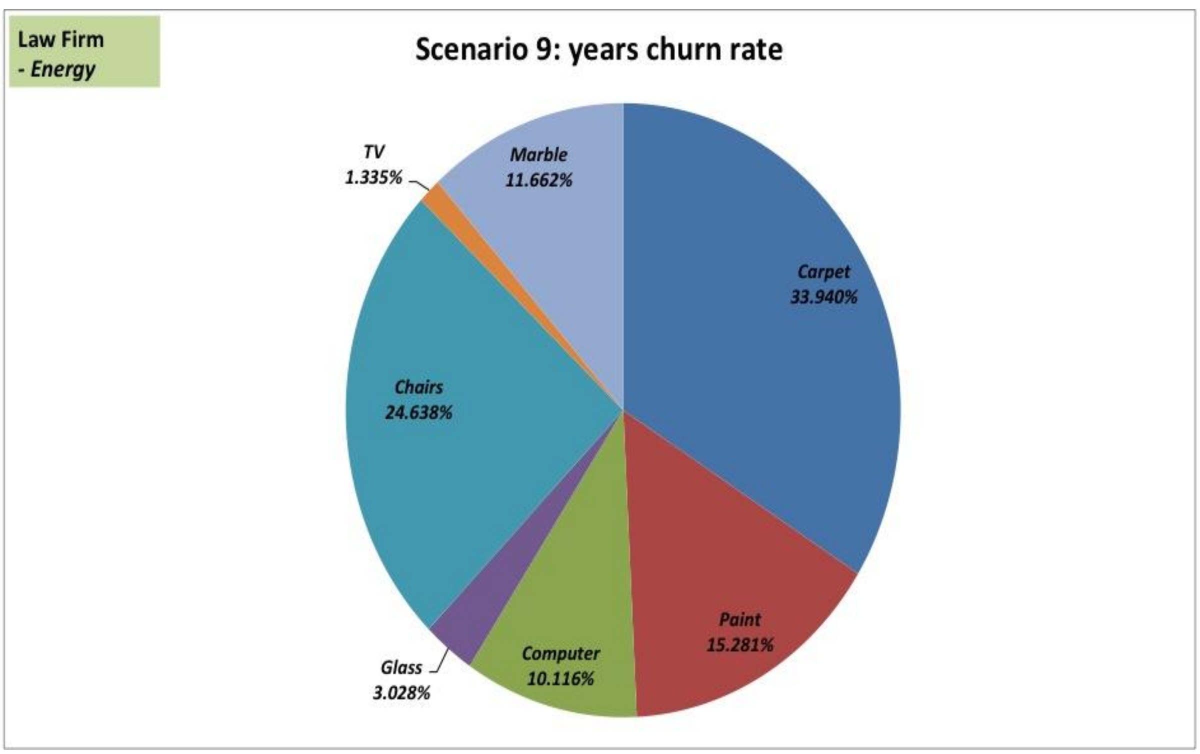

Law Firm
- Energy
Scenario 7: No specified time frame
Marble
14.153%
TV
0.810%
Carpet
41.189%
Chairs
29.901%
Paint
6.182%
Glass
3.674%
Computer
4.092%

21 (H)



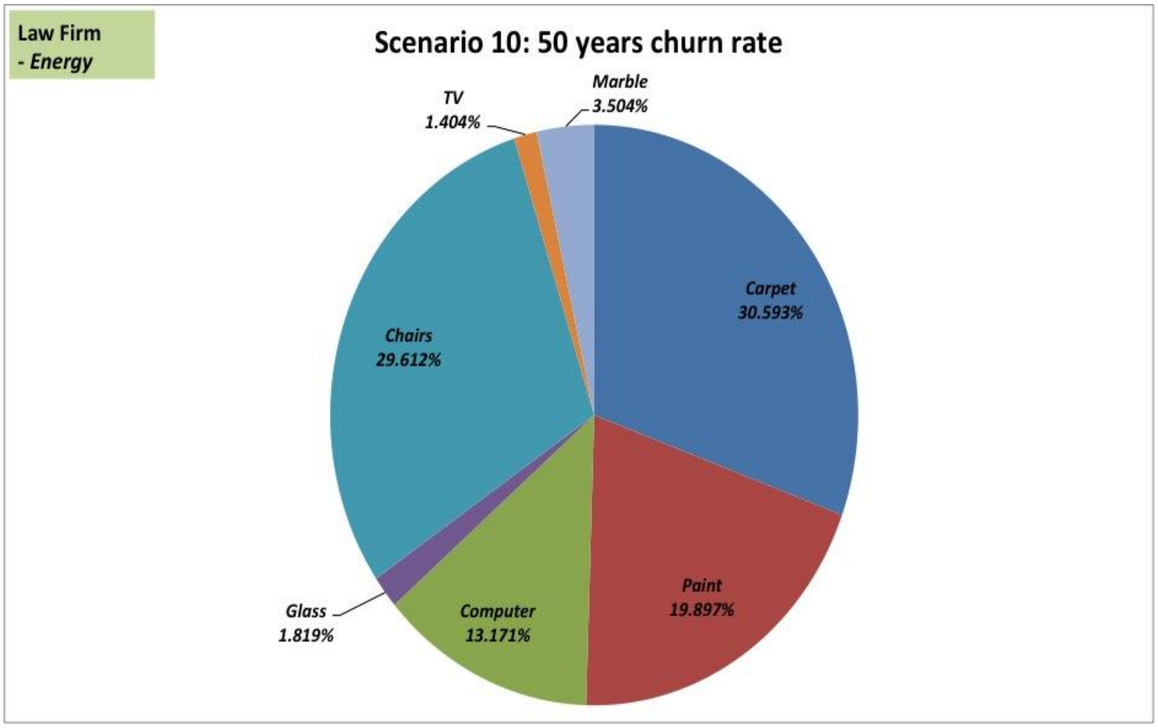
Law Firm
- Energy
Scenario 8: 5 years churn rate
TV
0.735%
Marble
12.834%
Carpet
37.351%
Chairs
27.115%
Paint
11.212%
Glass
3.332%
Computer
7.422%

21 (I)



Law Firm
- Energy
Scenario 9: years churn rate
TV
1.335%
Marble
11.662%
Carpet
33.940%
Chairs
24.638%
Paint
15.281%
Glass
3.028%
Computer
10.116%

21 (J)



21 (K)

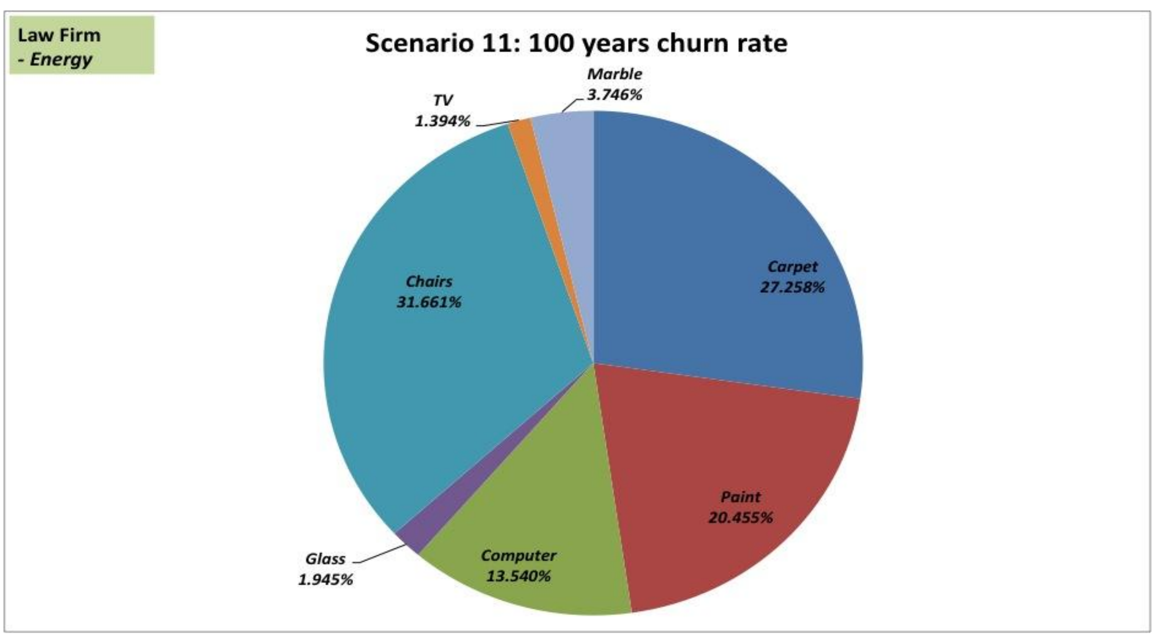
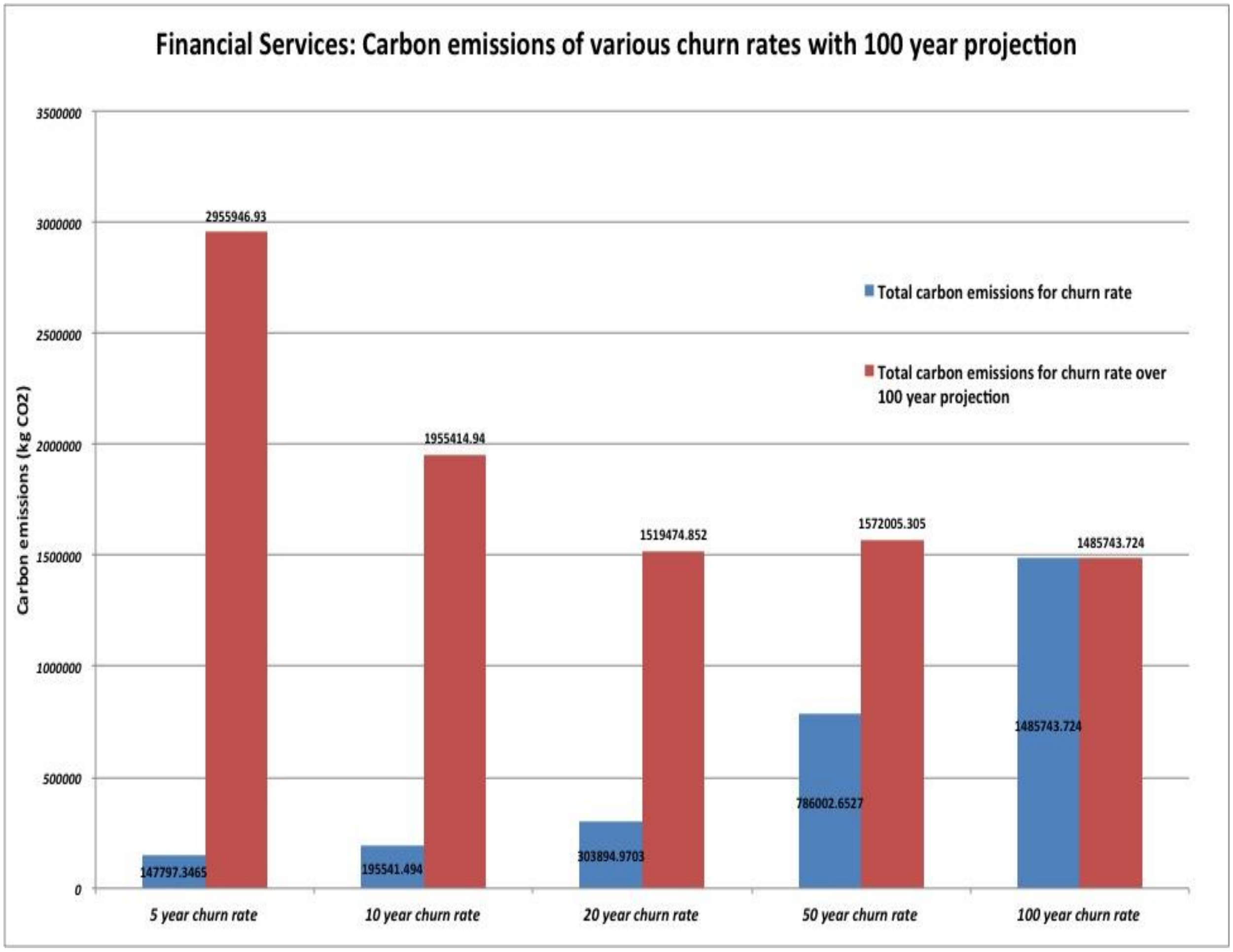


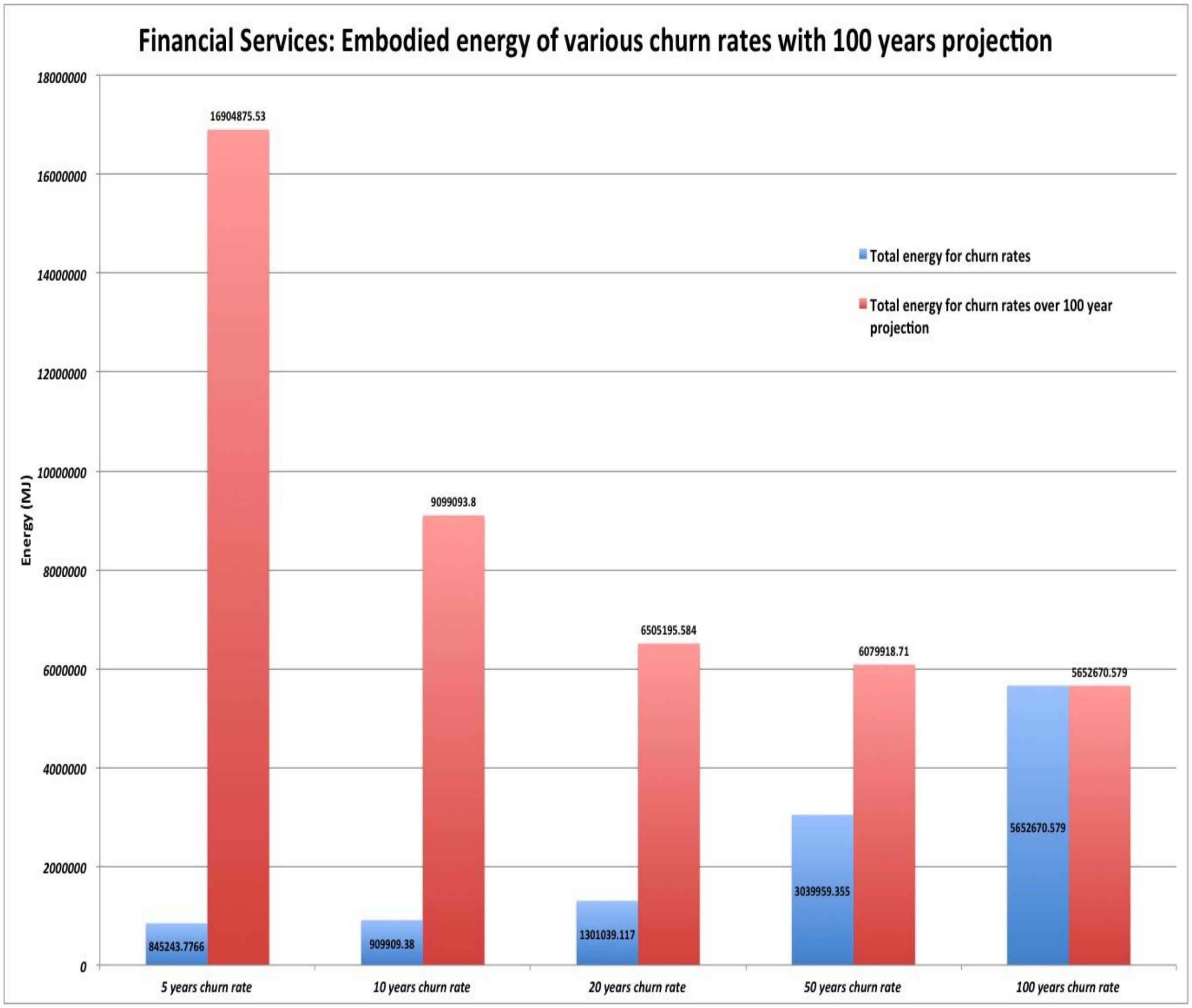
Figure 21. These pie charts are Energy data for the law firm scenarios. Each pie chart shows the percent contribution of each component for each scenario.

22 (A)



Financial Services: Carbon emissions of various churn rates with 100 year projection
Carbon emissions (kg CO2)
3500000
3000000
2500000
2000000
1500000
1000000
500000
0
Total carbon emissions for churn rate
Total carbon emissions for churn rate over 100 year projection
2955946.93
147797.3465
1955414.94
195541.494
1519474.852
303894.9703
1572005.305
786002.6527
1485743.724
1485743.724
5 year churn rate
10 year churn rate
20 year churn rate
50 year churn rate
100 year churn rate

22 (B)



Financial Services: Embodied energy of various churn rates with 100 years projection
Energy (MJ)
18000000
16000000
14000000
12000000
10000000
8000000
6000000
4000000
2000000
0
Total energy for churn rates
Total energy for churn rates over 100 year projection
16904875.53
9099093.8
6505195.584
6079918.71
5652670.579
845243.7766
909909.38
1301039.117
3039959.355
5652670.579
5 years churn rate
10 years churn rate
20 years churn rate
50 years churn rate
100 years churn rate

22 (C)

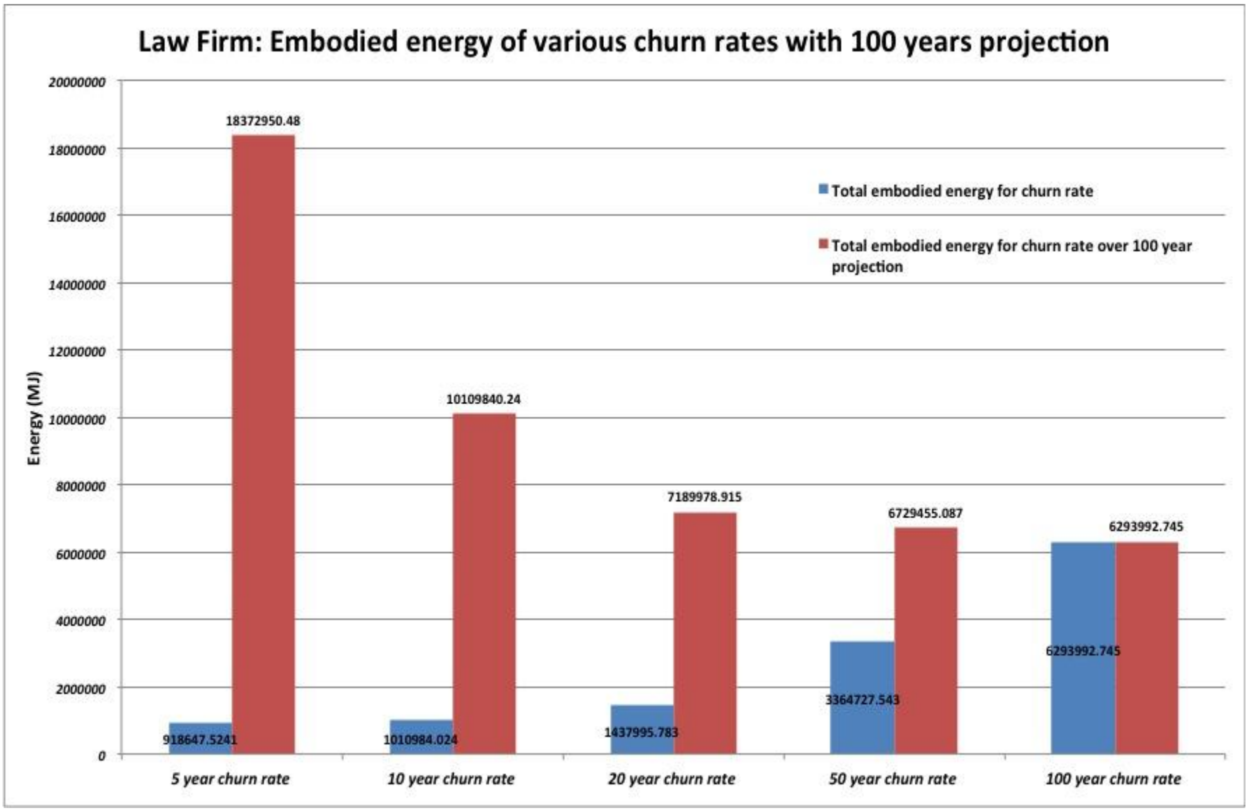


Figure 22. In these graphs, the impacts of various churn rates (represented in blue) are compared side by side over a hypothetical 100 year period (represented in red). The blue bar represents the impact of one churn of a set of materials, and the red bar graph coupled with it represents the total amount of Carbon or energy embodied over a 100 year period due to that churn rate. For example, the first blue bar graph displays the impact of a five year churn rate in five years, or one churn. Alongside it, the impact associated with that churn rate over 100 years is shown, and is therefore twenty times the blue bar.

10.3 Appendix C: Hotel Scenarios

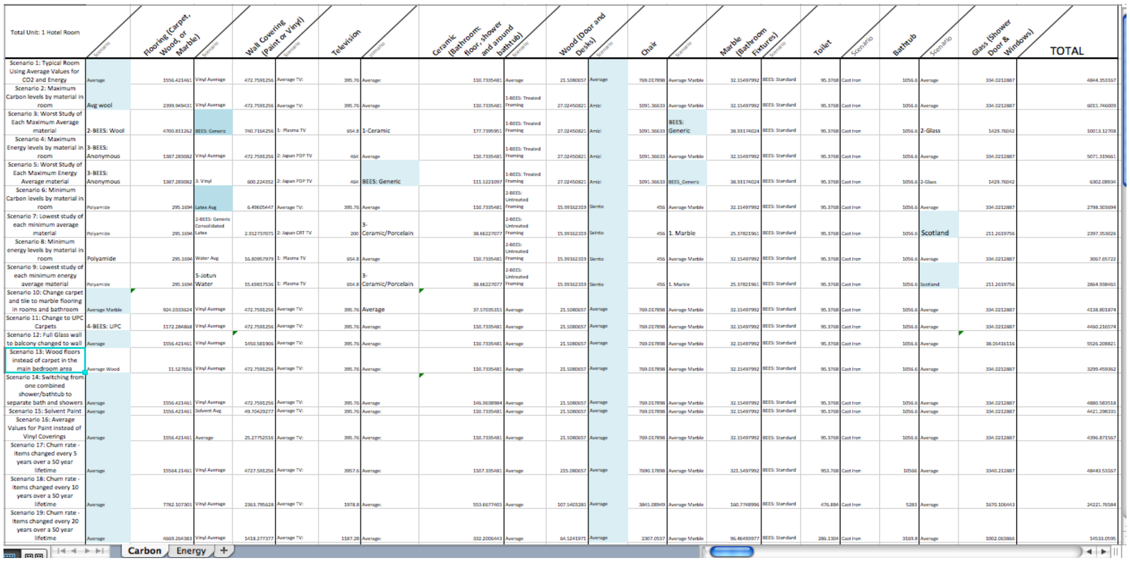


Figure 23. This is a screenshot of our excel database for the carbon emitted in our hotel scenarios. The scenarios range from the original hotel room, maximums and minimums, and structural and material changes.

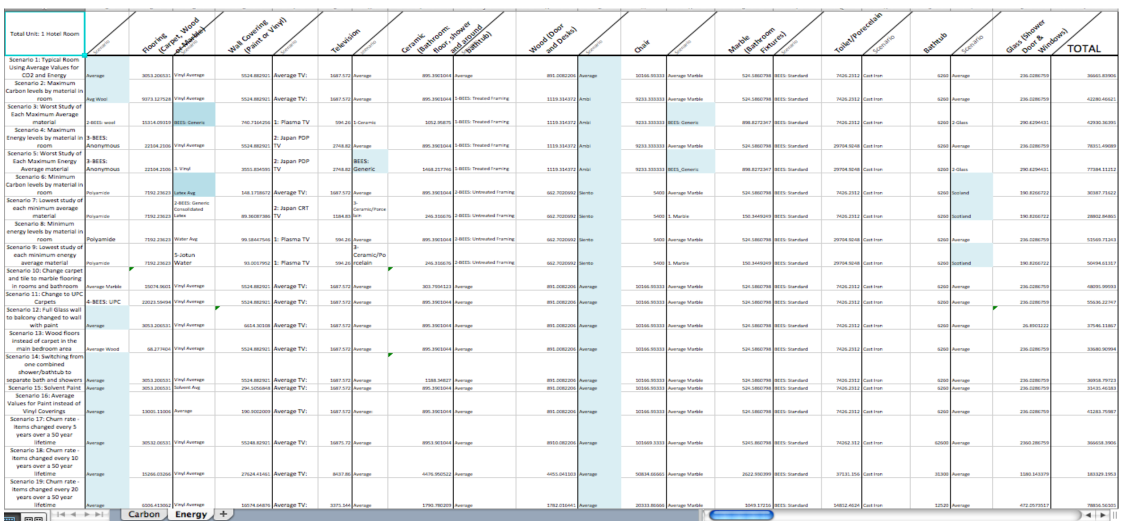
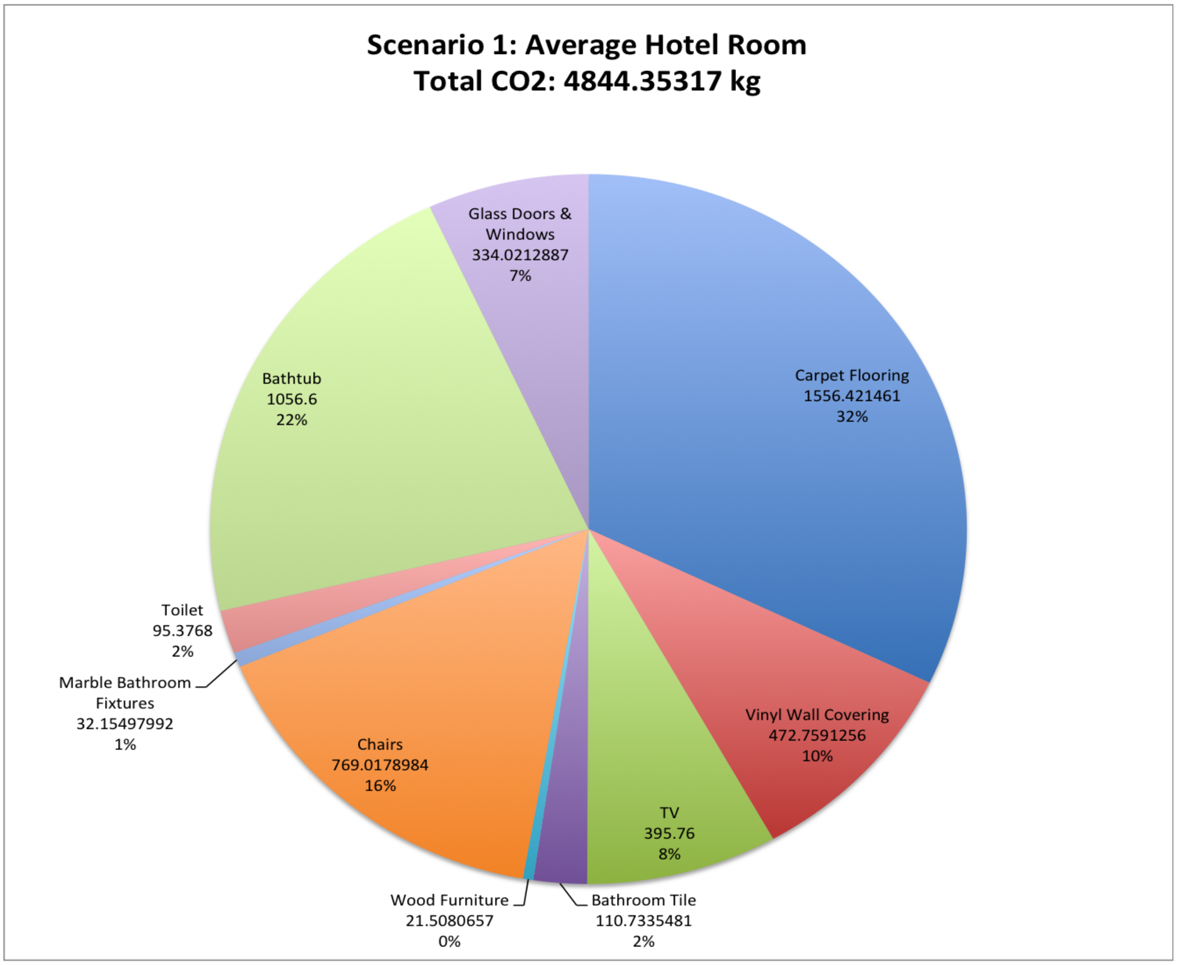


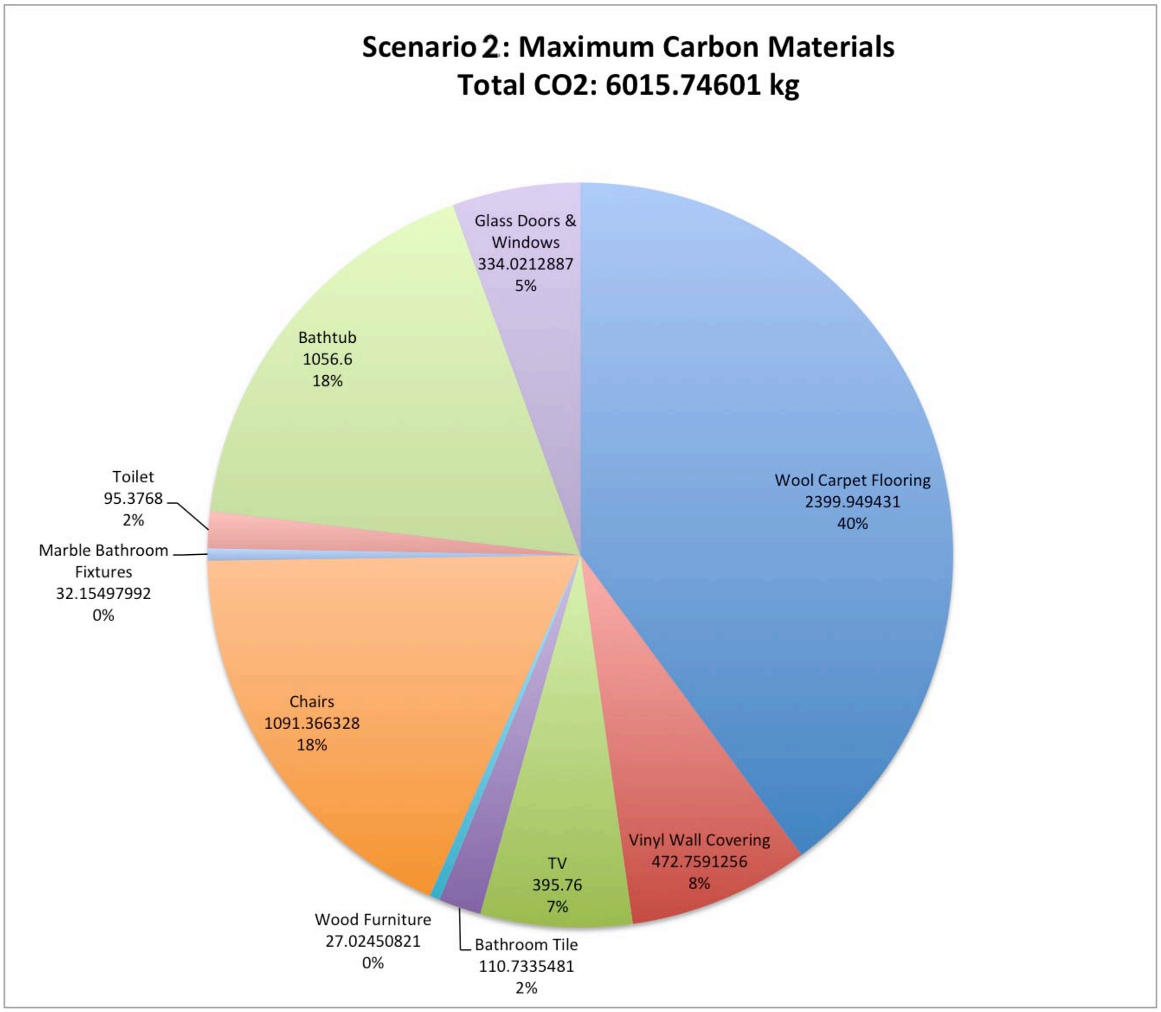
Figure 24. A screenshot of our excel database for the energy usage in our hotel scenarios. The scenarios range from the original hotel room, maximums and minimums, and structural and material changes.

25 (A)

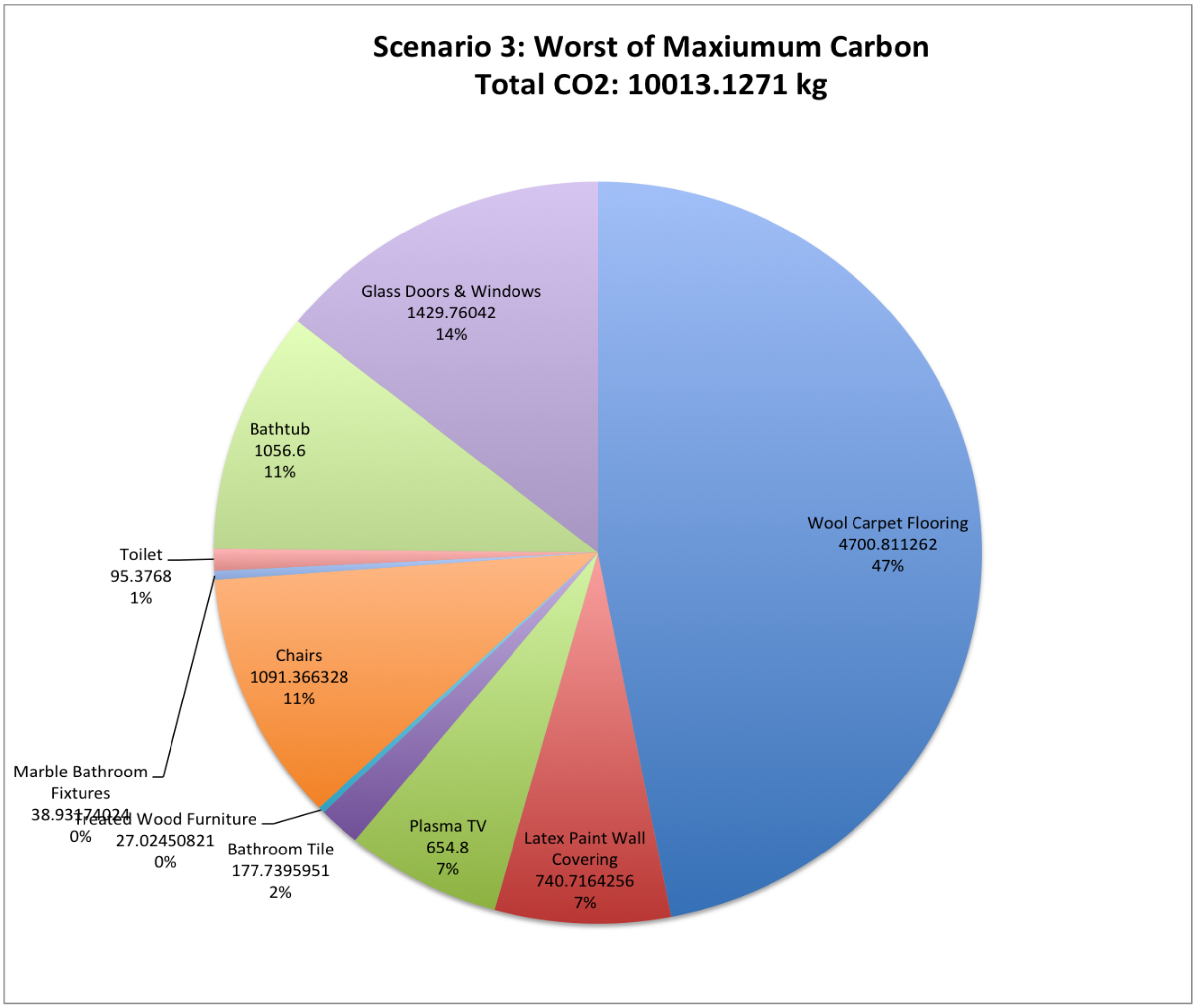


Scenario 1: Average Hotel Room
Total CO2: 4844.35317 kg
Glass Doors & Windows 334.0212887 7%
Carpet Flooring 1556.421461 32%
Bathtub 1056.6 22%
Toilet 95.3768 2%
Marble Bathroom Fixtures 32.15497992 1%
Chairs 769.0178984 16%
Vinyl Wall Covering 472.7591256 10%
TV 395.76 8%
Wood Furniture 21.5080657 0%
Bathroom Tile 110.7335481 2%

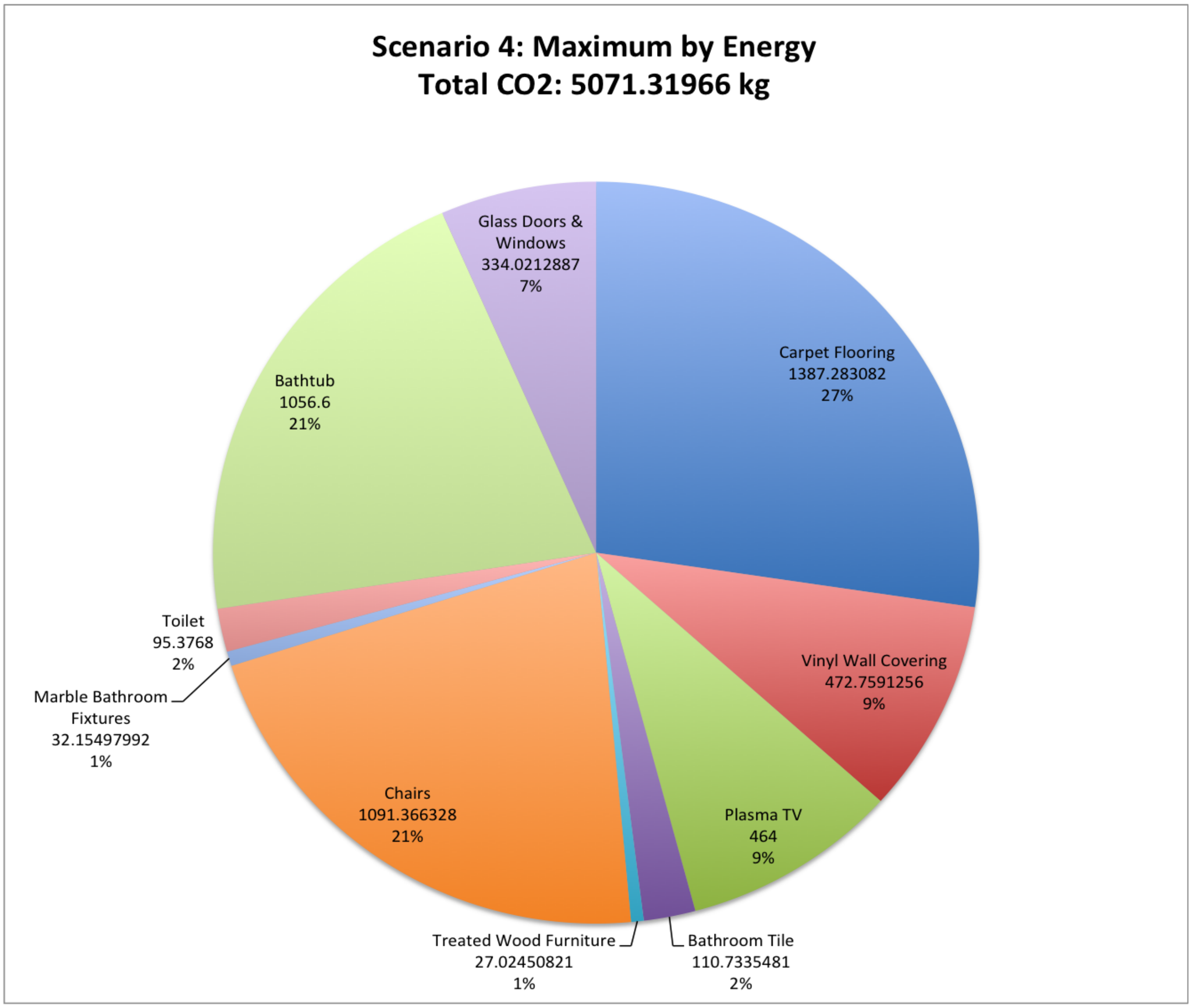
25 (B)


Scenario 2: Maximum Carbon Materials
Total CO2: 6015.74601 kg
Glass Doors & Windows
334.0212887
5%
Bathtub
1056.6
18%
Toilet
95.3768
2%
Marble Bathroom Fixtures
32.15497992
0%
Chairs
1091.366328
18%
Wood Furniture
27.02450821
0%
Bathroom Tile
110.7335481
2%
TV
395.76
7%
Vinyl Wall Covering
472.7591256
8%
Wool Carpet Flooring
2399.949431
40%

25 (C)

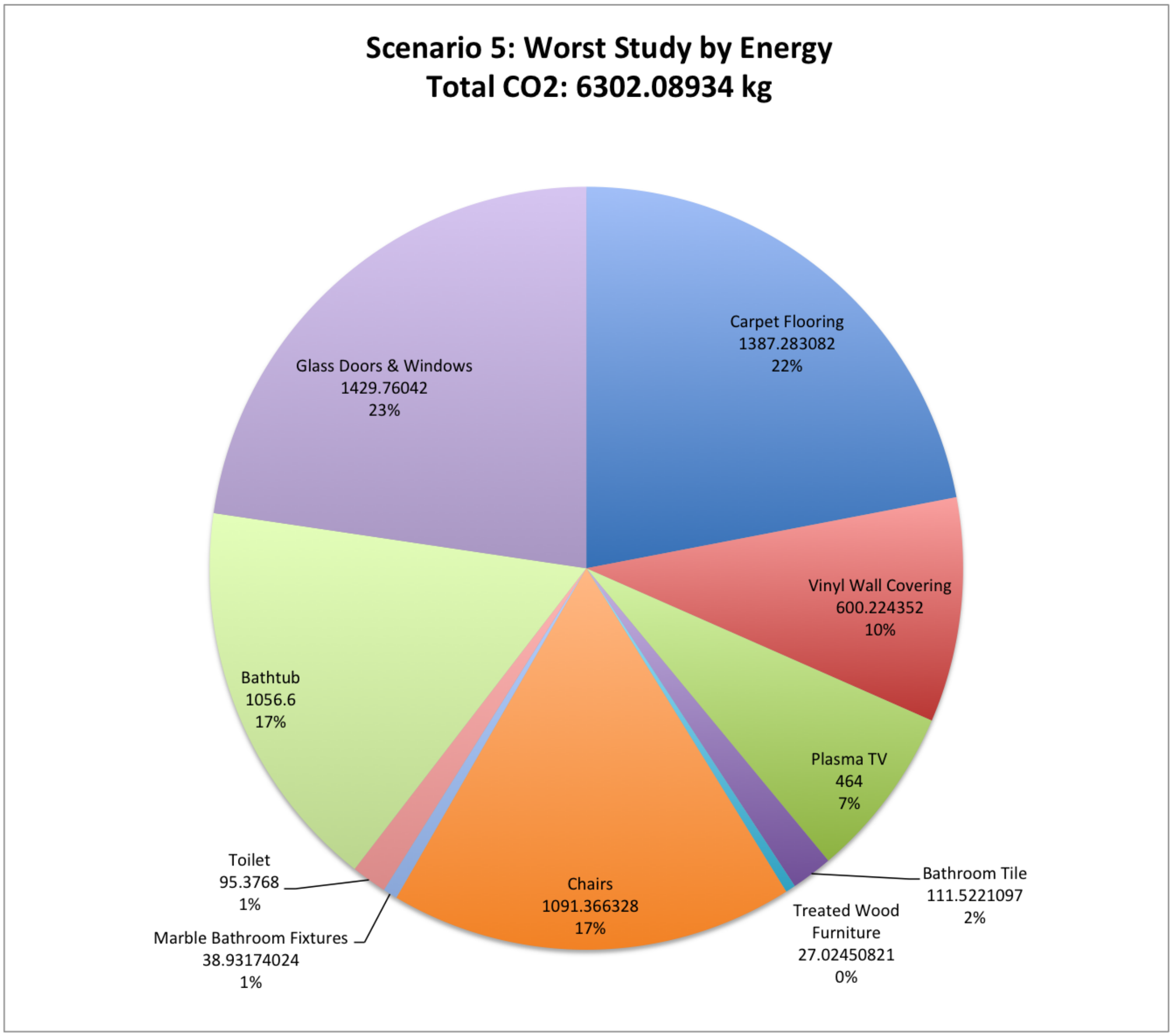

Scenario 3: Worst of Maxiumum Carbon
Total CO2: 10013.1271 kg
Glass Doors & Windows
1429.76042
14%
Bathtub
1056.6
11%
Wool Carpet Flooring
4700.811262
47%
Toilet
95.3768
1%
Chairs
1091.366328
11%
Marble Bathroom Fixtures
38.93174024
0%
Treated Wood Furniture
27.02450821
0%
Bathroom Tile
177.7395951
2%
Plasma TV
654.8
7%
Latex Paint Wall Covering
740.7164256
7%

25 (D)

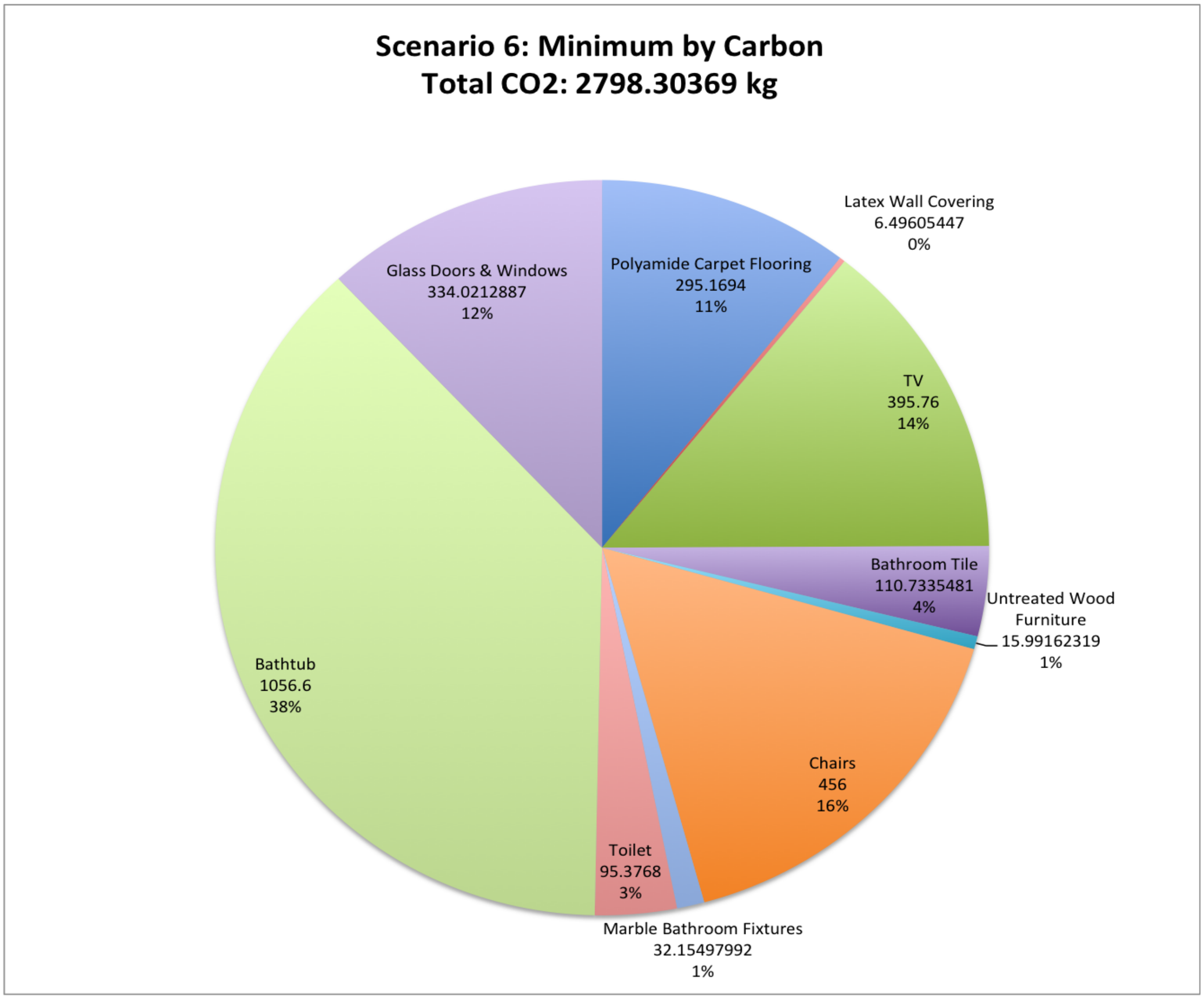


Scenario 4: Maximum by Energy
Total CO2: 5071.31966 kg
Glass Doors & Windows
334.0212887
7%
Carpet Flooring
1387.283082
27%
Bathtub
1056.6
21%
Toilet
95.3768
2%
Marble Bathroom Fixtures
32.15497992
1%
Vinyl Wall Covering
472.7591256
9%
Chairs
1091.366328
21%
Plasma TV
464
9%
Treated Wood Furniture
27.02450821
1%
Bathroom Tile
110.7335481
2%

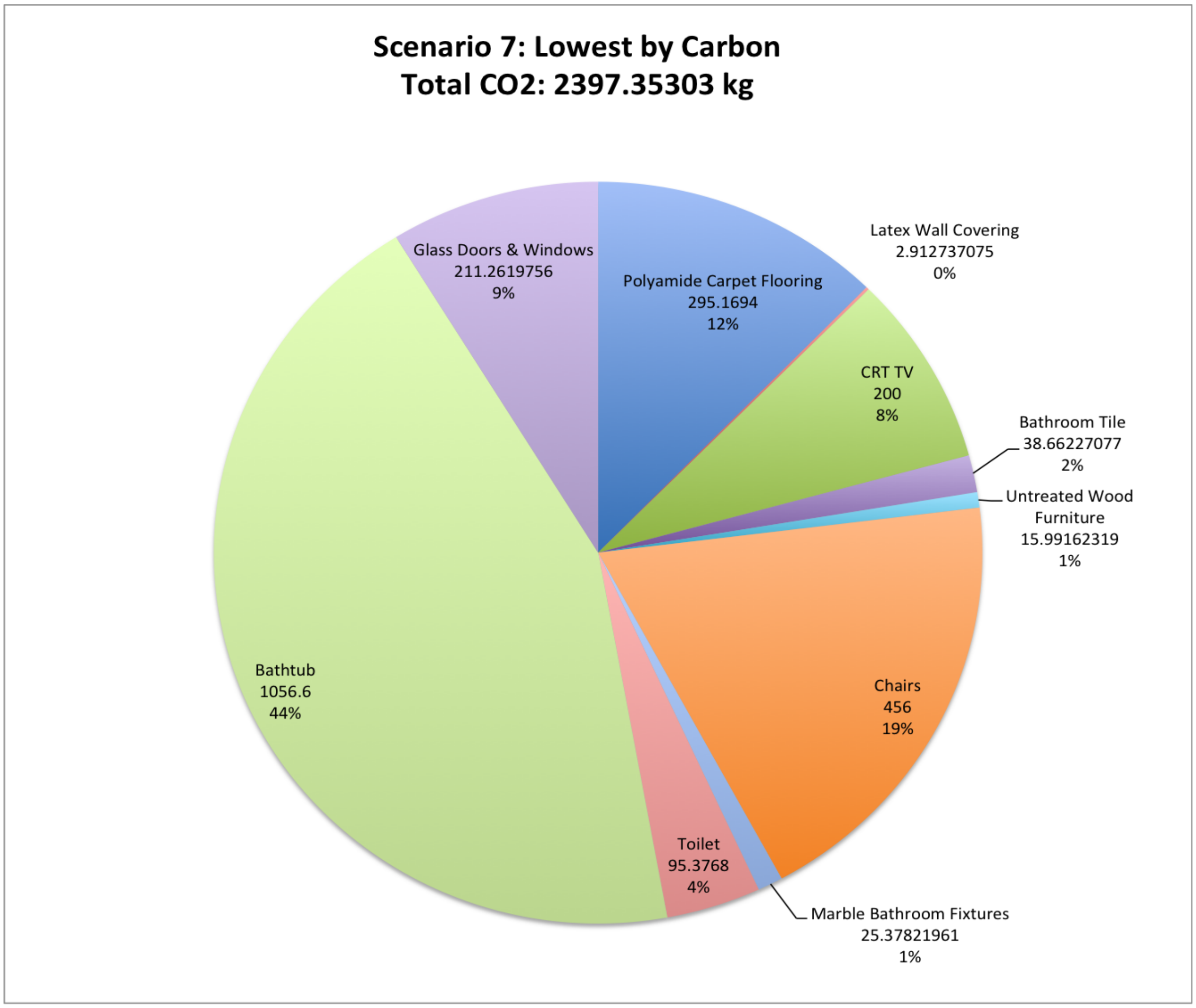
25 (E)


Scenario 5: Worst Study by Energy
Total CO2: 6302.08934 kg
Carpet Flooring
1387.283082
22%
Glass Doors & Windows
1429.76042
23%
Vinyl Wall Covering
600.224352
10%
Bathtub
1056.6
17%
Plasma TV
464
7%
Toilet
95.3768
1%
Chairs
1091.366328
17%
Bathroom Tile
111.5221097
2%
Treated Wood
Furniture
27.02450821
0%
Marble Bathroom Fixtures
38.93174024
1%

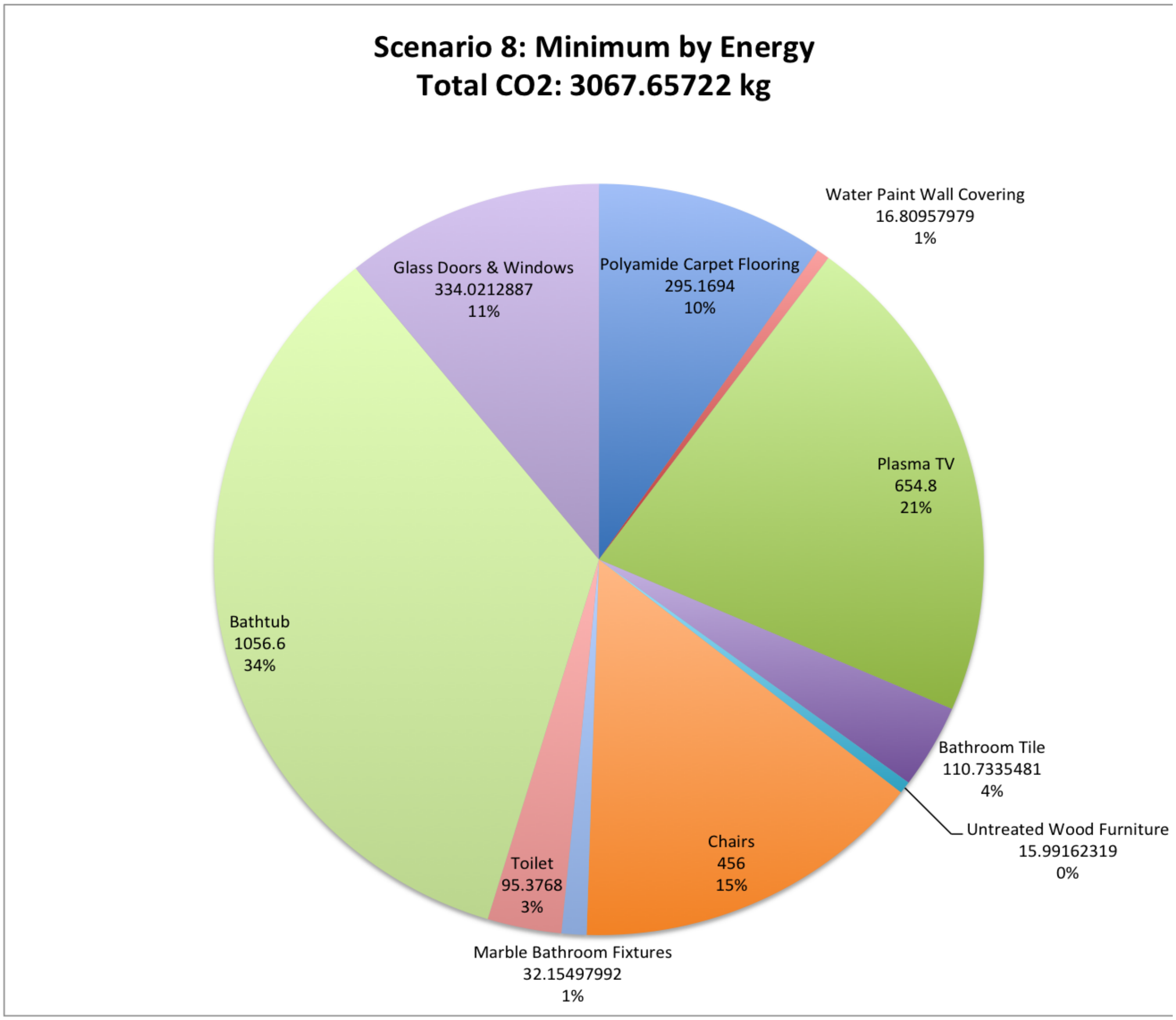
25 (F)


Scenario 6: Minimum by Carbon
Total CO2: 2798.30369 kg
Latex Wall Covering
6.49605447
0%
Polyamide Carpet Flooring
295.1694
11%
Glass Doors & Windows
334.0212887
12%
TV
395.76
14%
Bathroom Tile
110.7335481
4%
Untreated Wood
Furniture
15.99162319
1%
Bathtub
1056.6
38%
Chairs
456
16%
Toilet
95.3768
3%
Marble Bathroom Fixtures
32.15497992
1%

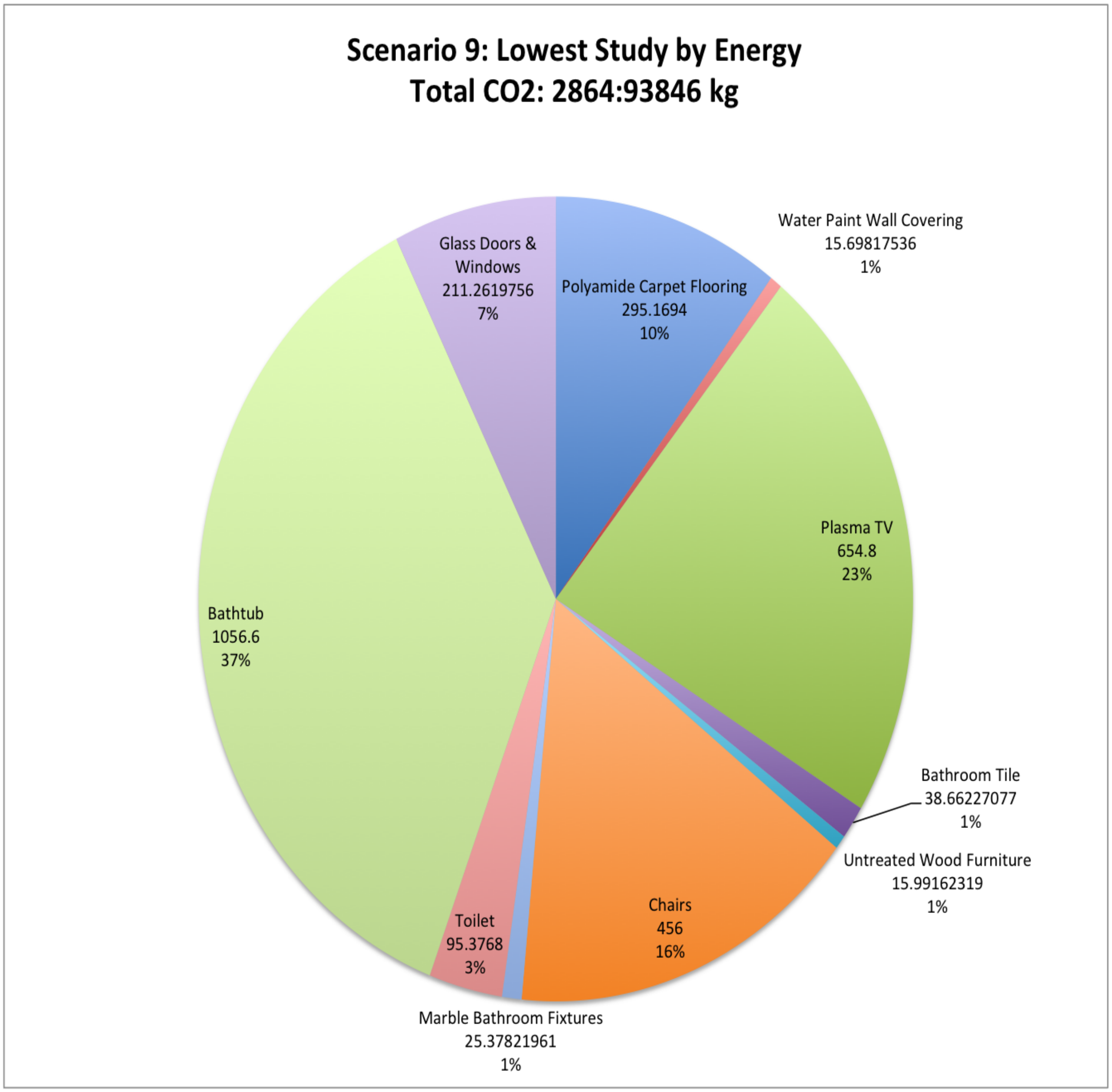
25 (G)


Scenario 7: Lowest by Carbon
Total CO2: 2397.35303 kg
Glass Doors & Windows
211.2619756
9%
Polyamide Carpet Flooring
295.1694
12%
Latex Wall Covering
2.912737075
0%
CRT TV
200
8%
Bathroom Tile
38.66227077
2%
Untreated Wood
Furniture
15.99162319
1%
Chairs
456
19%
Marble Bathroom Fixtures
25.37821961
1%
Toilet
95.3768
4%
Bathtub
1056.6
44%

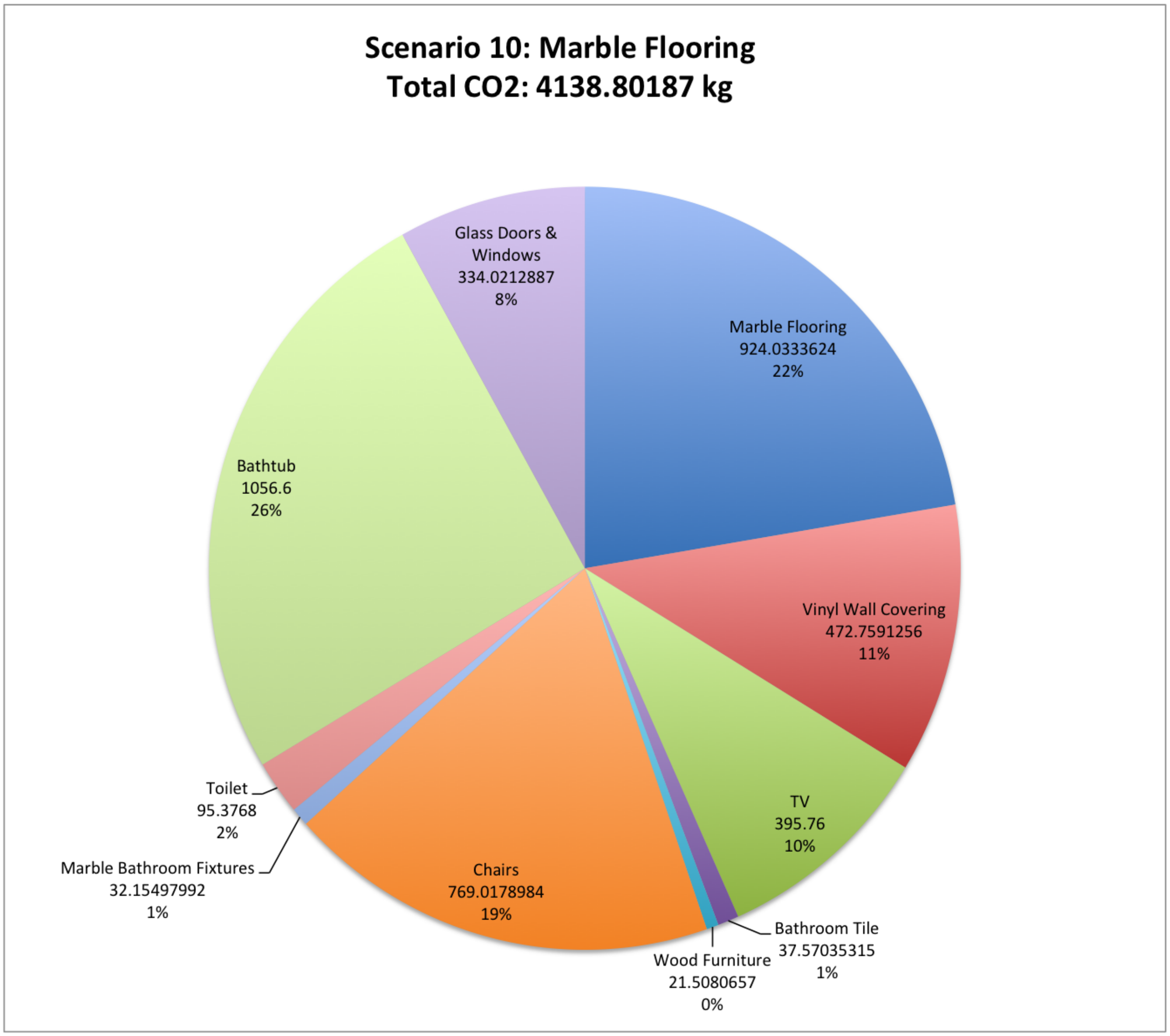
25 (H)


Scenario 8: Minimum by Energy
Total CO2: 3067.65722 kg
Water Paint Wall Covering
16.80957979
1%
Glass Doors & Windows
334.0212887
11%
Polyamide Carpet Flooring
295.1694
10%
Plasma TV
654.8
21%
Bathtub
1056.6
34%
Bathroom Tile
110.7335481
4%
Untreated Wood Furniture
15.99162319
0%
Chairs
456
15%
Toilet
95.3768
3%
Marble Bathroom Fixtures
32.15497992
1%

25 (I)

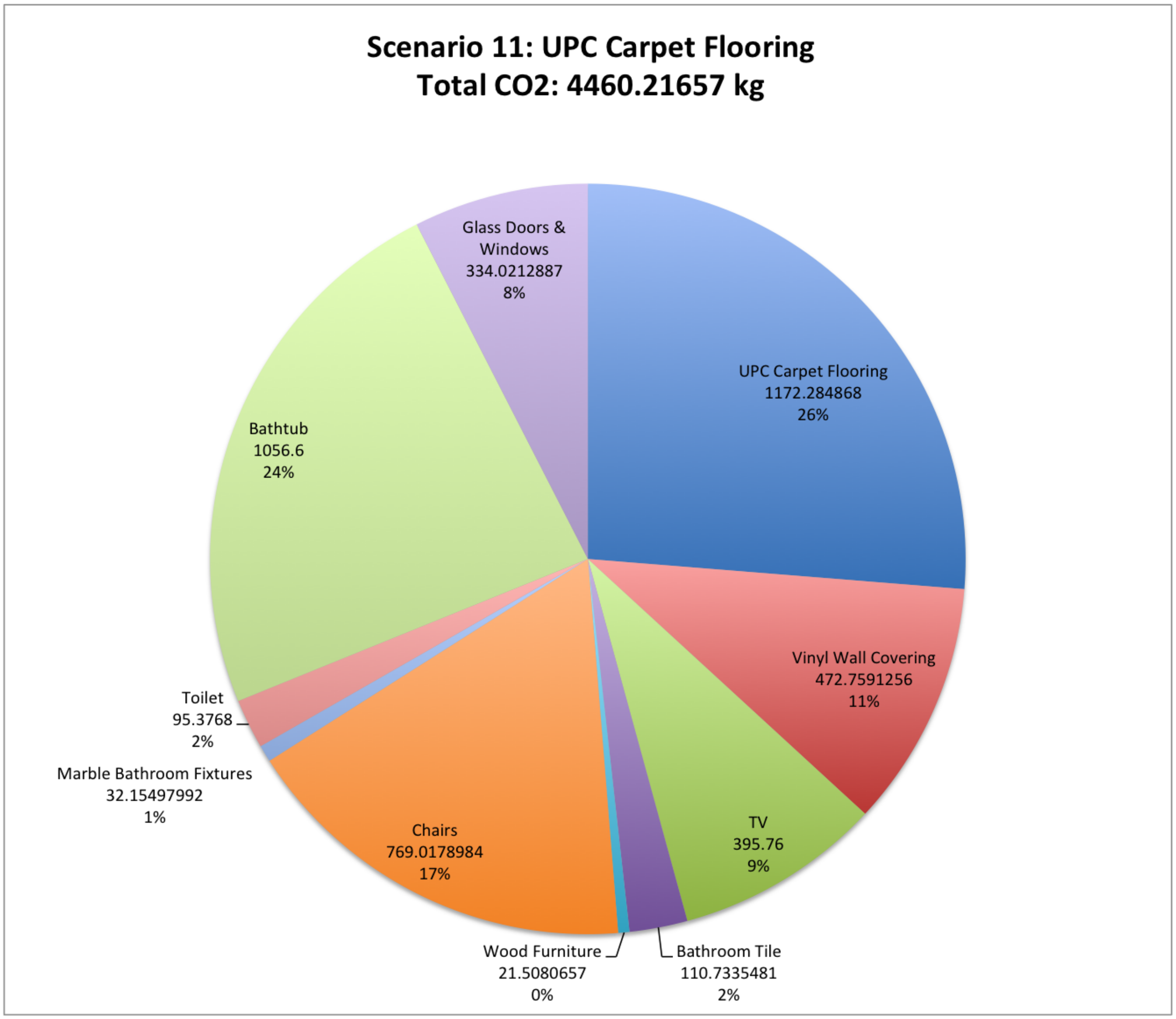

Scenario 9: Lowest Study by Energy
Total CO2: 2864:93846 kg
Water Paint Wall Covering
15.69817536
1%
Glass Doors & Windows
211.2619756
7%
Polyamide Carpet Flooring
295.1694
10%
Plasma TV
654.8
23%
Bathtub
1056.6
37%
Bathroom Tile
38.66227077
1%
Untreated Wood Furniture
15.99162319
1%
Chairs
456
16%
Toilet
95.3768
3%
Marble Bathroom Fixtures
25.37821961
1%

25 (J)



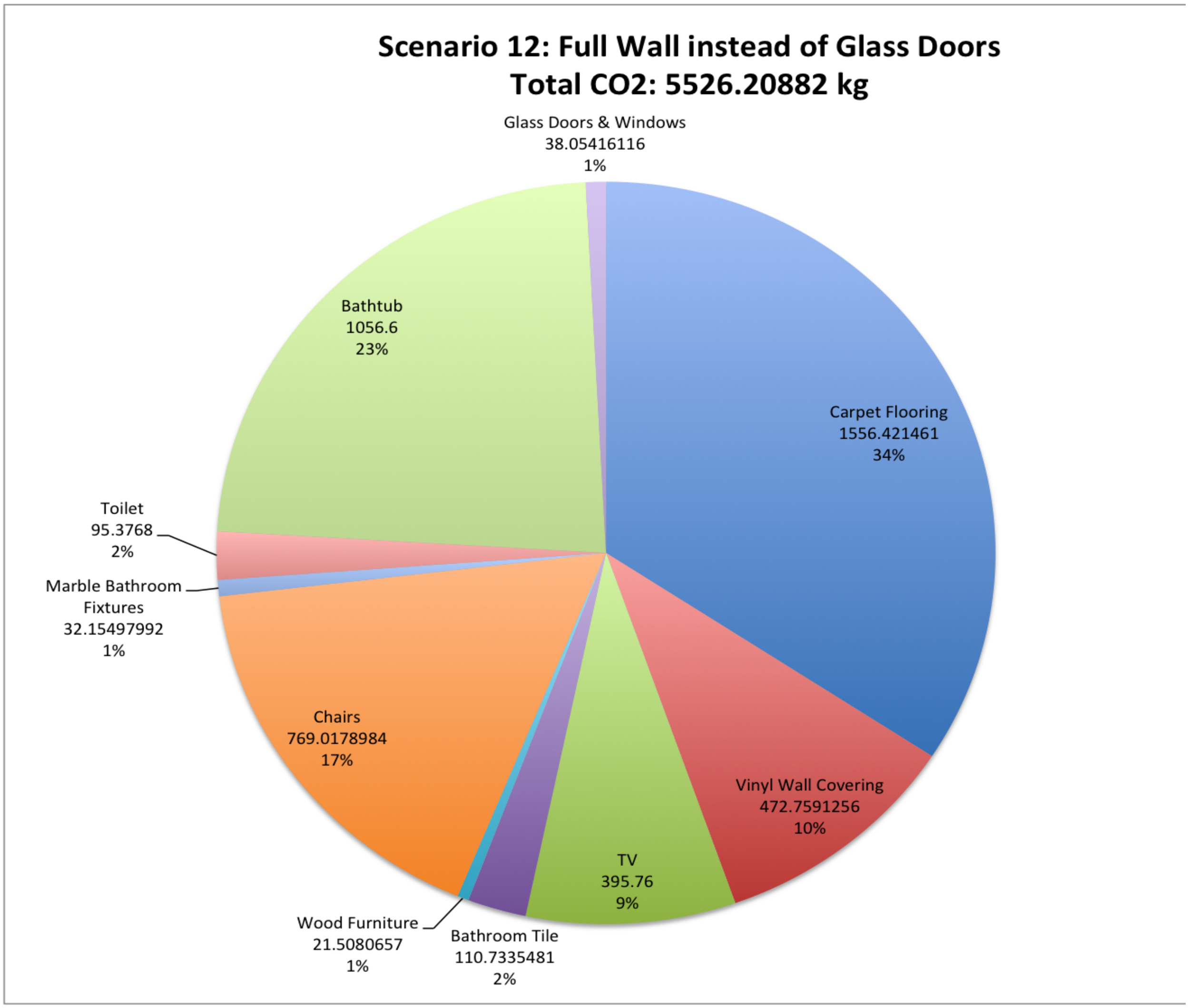
Scenario 10: Marble Flooring
Total CO2: 4138.80187 kg
Glass Doors & Windows
334.0212887
8%
Marble Flooring
924.0333624
22%
Bathtub
1056.6
26%
Vinyl Wall Covering
472.7591256
11%
Toilet
95.3768
2%
TV
395.76
10%
Marble Bathroom Fixtures
32.15497992
1%
Chairs
769.0178984
19%
Bathroom Tile
37.57035315
1%
Wood Furniture
21.5080657
0%

25 (K)

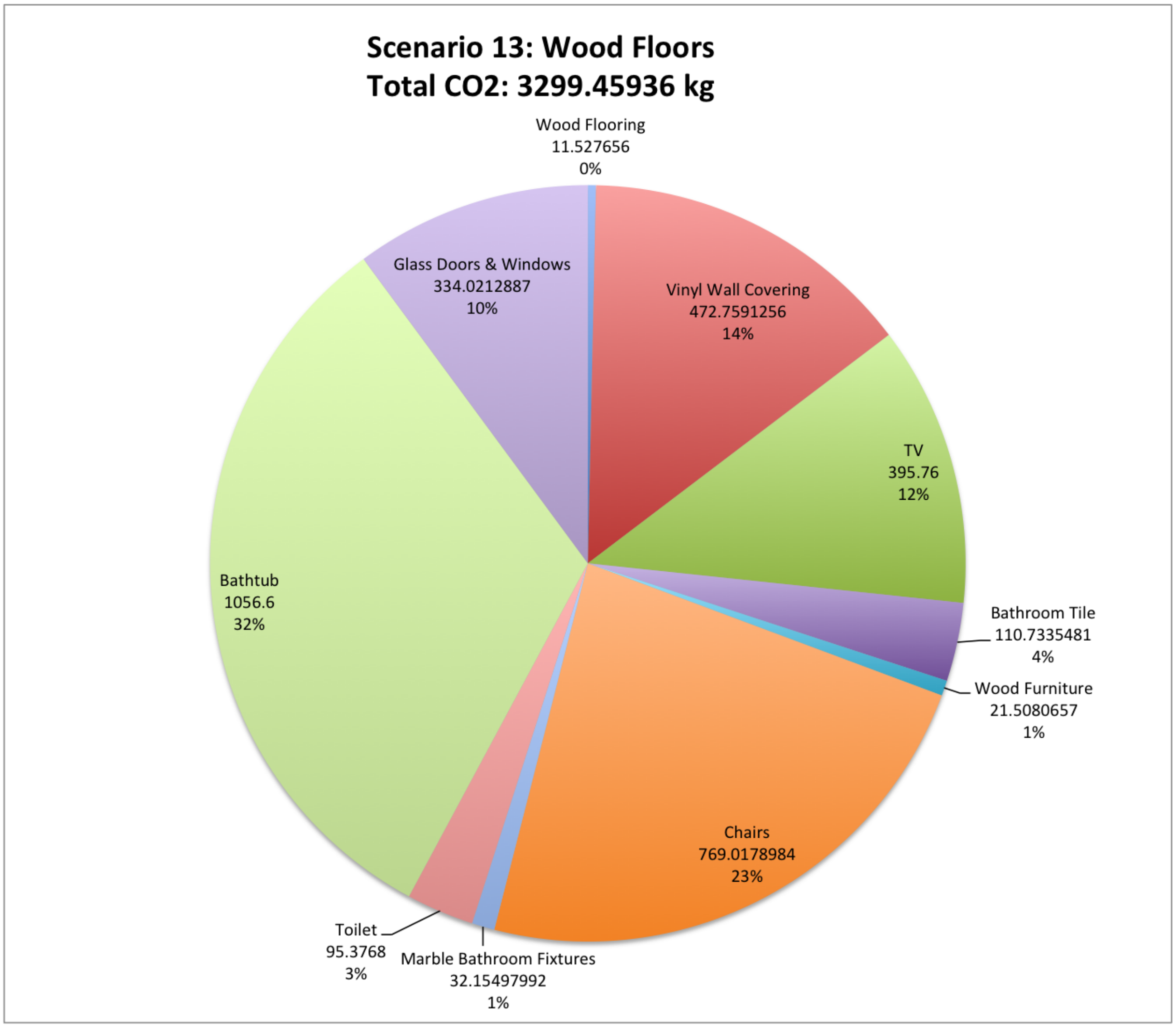


Scenario 11: UPC Carpet Flooring
Total CO2: 4460.21657 kg
Glass Doors & Windows
334.0212887
8%
UPC Carpet Flooring
1172.284868
26%
Bathtub
1056.6
24%
Vinyl Wall Covering
472.7591256
11%
Toilet
95.3768
2%
Marble Bathroom Fixtures
32.15497992
1%
TV
395.76
9%
Chairs
769.0178984
17%
Wood Furniture
21.5080657
0%
Bathroom Tile
110.7335481
2%

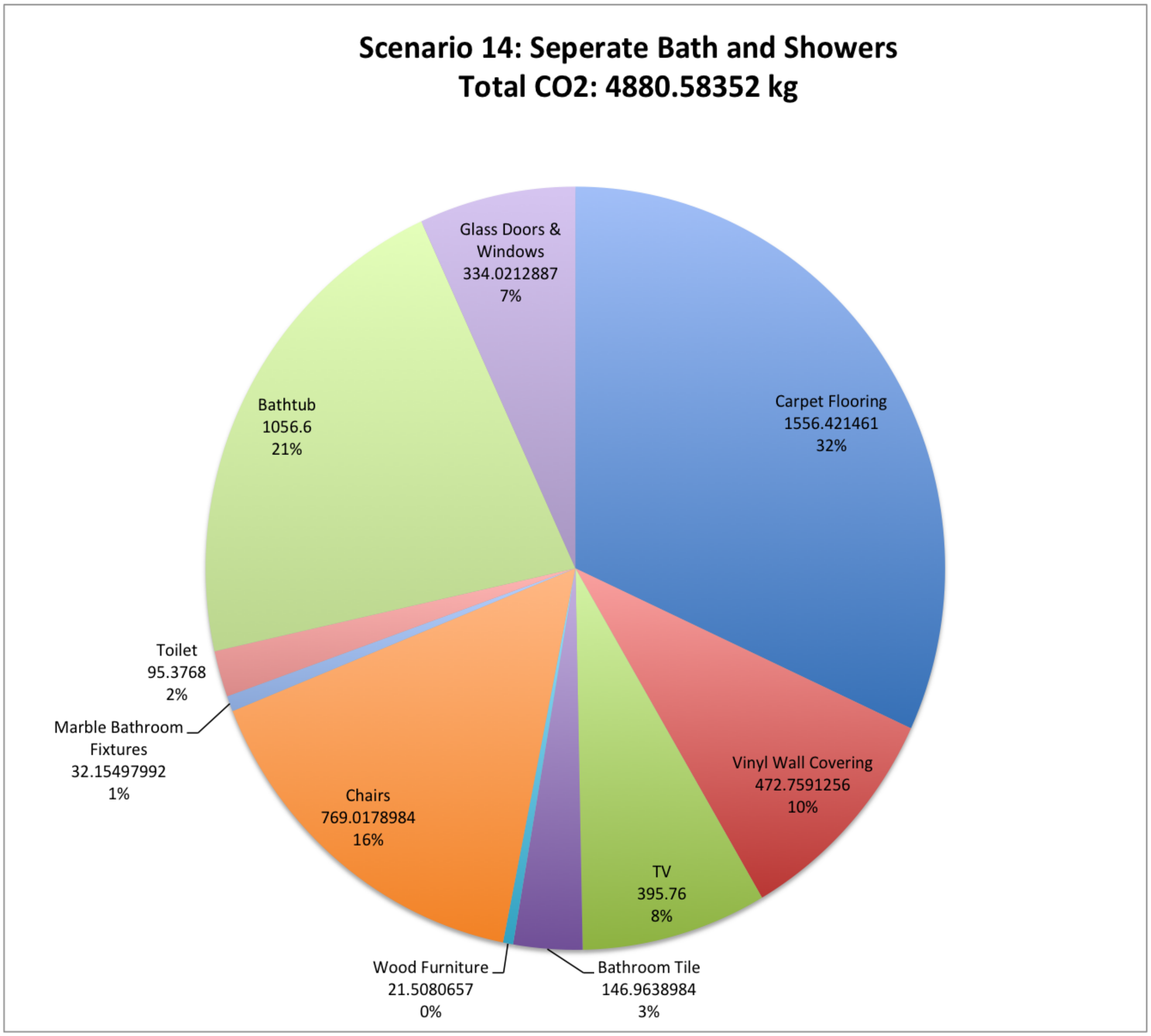
25 (L)


Scenario 12: Full Wall instead of Glass Doors
Total CO2: 5526.20882 kg
Glass Doors & Windows
38.05416116
1%
Carpet Flooring
1556.421461
34%
Vinyl Wall Covering
472.7591256
10%
TV
395.76
9%
Bathroom Tile
110.7335481
2%
Wood Furniture
21.5080657
1%
Chairs
769.0178984
17%
Marble Bathroom
Fixtures
32.15497992
1%
Toilet
95.3768
2%
Bathtub
1056.6
23%

25 (M)

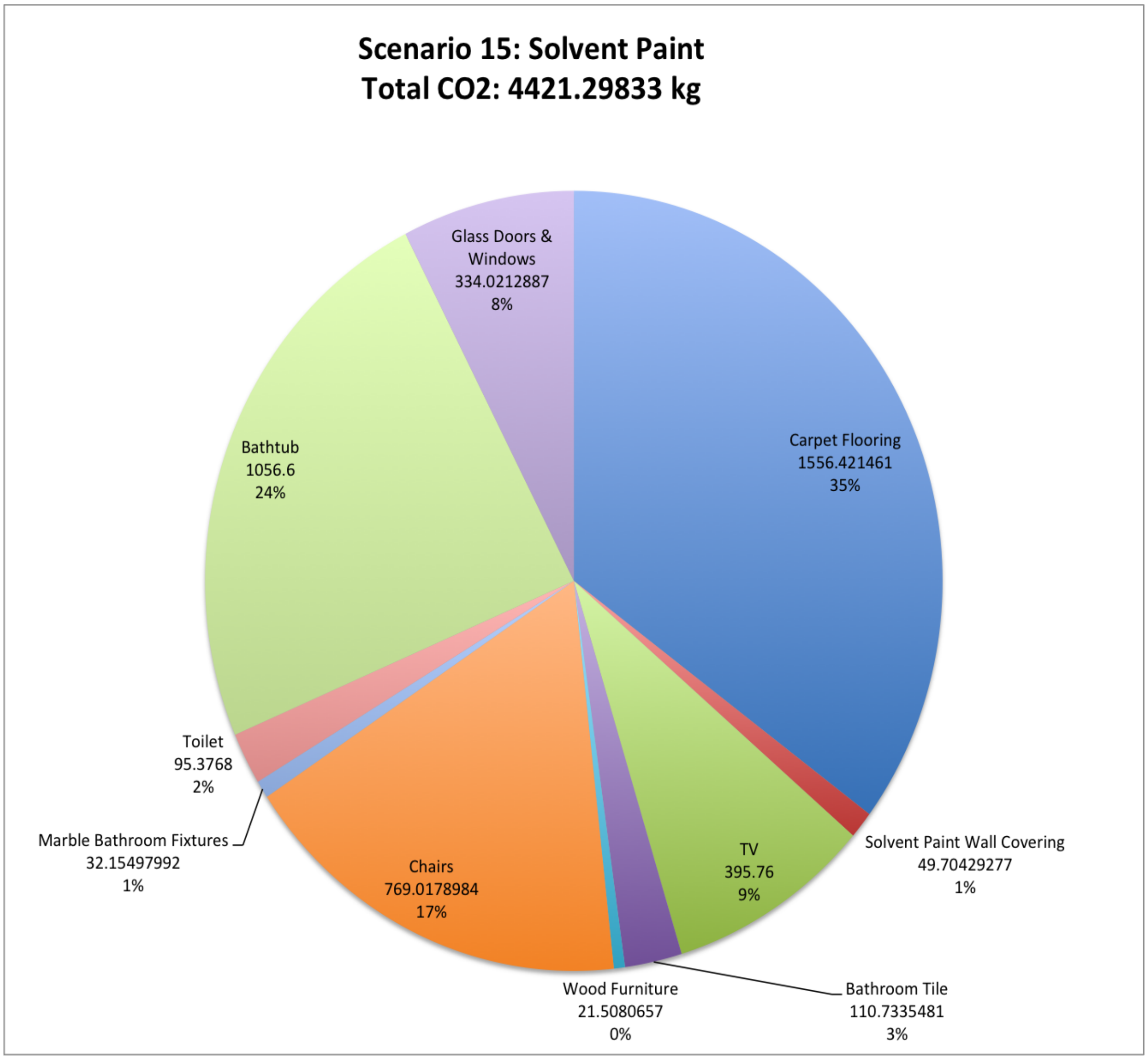

Scenario 13: Wood Floors
Total CO2: 3299.45936 kg
Wood Flooring
11.527656
0%
Vinyl Wall Covering
472.7591256
14%
TV
395.76
12%
Bathroom Tile
110.7335481
4%
Wood Furniture
21.5080657
1%
Chairs
769.0178984
23%
Marble Bathroom Fixtures
32.15497992
1%
Toilet
95.3768
3%
Bathtub
1056.6
32%
Glass Doors & Windows
334.0212887
10%

25 (N)



Scenario 14: Seperate Bath and Showers
Total CO2: 4880.58352 kg
Glass Doors & Windows
334.0212887
7%
Carpet Flooring
1556.421461
32%
Bathtub
1056.6
21%
Toilet
95.3768
2%
Marble Bathroom Fixtures
32.15497992
1%
Vinyl Wall Covering
472.7591256
10%
Chairs
769.0178984
16%
TV
395.76
8%
Wood Furniture
21.5080657
0%
Bathroom Tile
146.9638984
3%

25 (O)



Scenario 15: Solvent Paint
Total CO2: 4421.29833 kg
Glass Doors & Windows 334.0212887 8%
Carpet Flooring 1556.421461 35%
Bathtub 1056.6 24%
Toilet 95.3768 2%
Marble Bathroom Fixtures 32.15497992 1%
Chairs 769.0178984 17%
TV 395.76 9%
Solvent Paint Wall Covering 49.70429277 1%
Wood Furniture 21.5080657 0%
Bathroom Tile 110.7335481 3%

25(P)

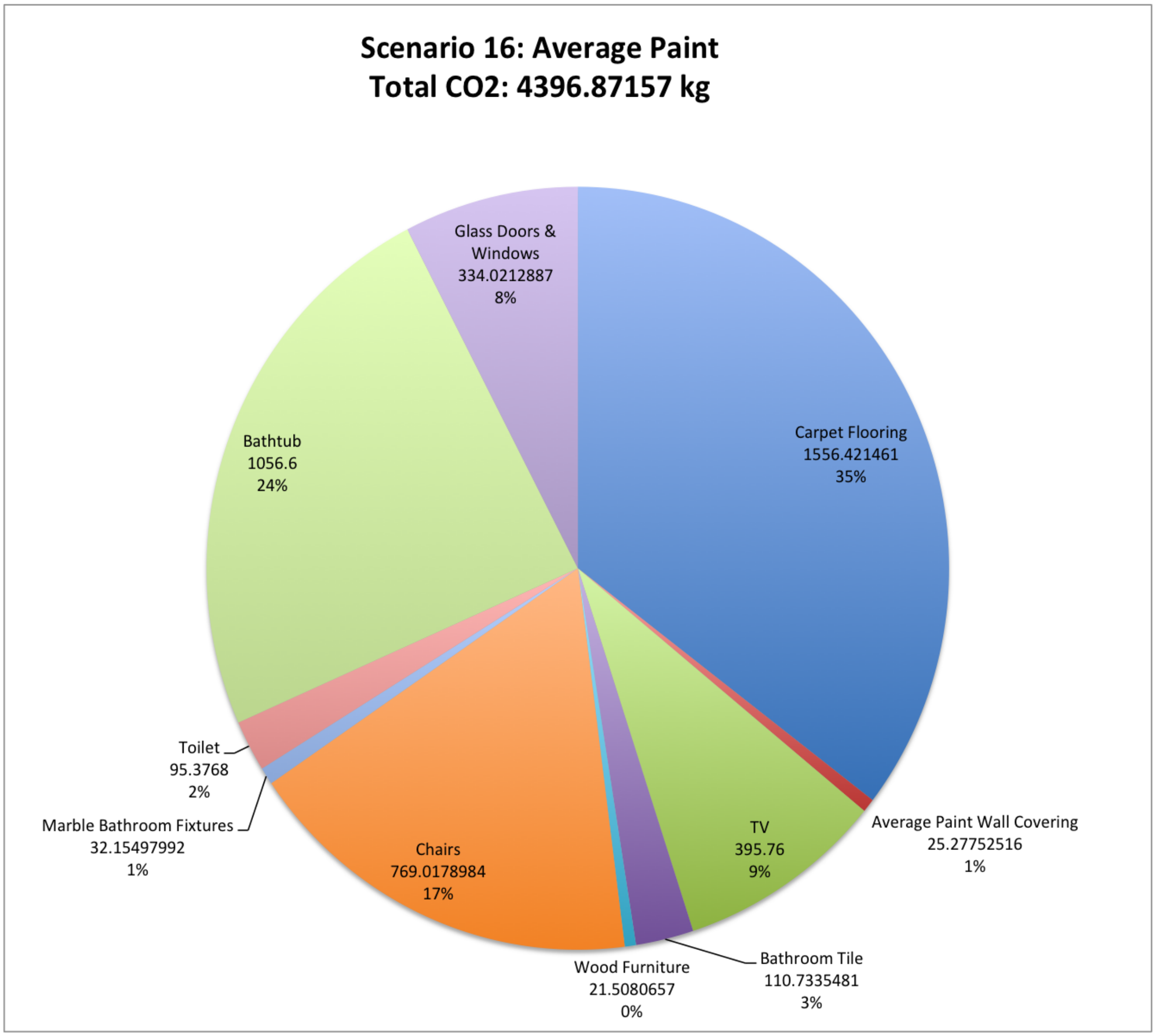
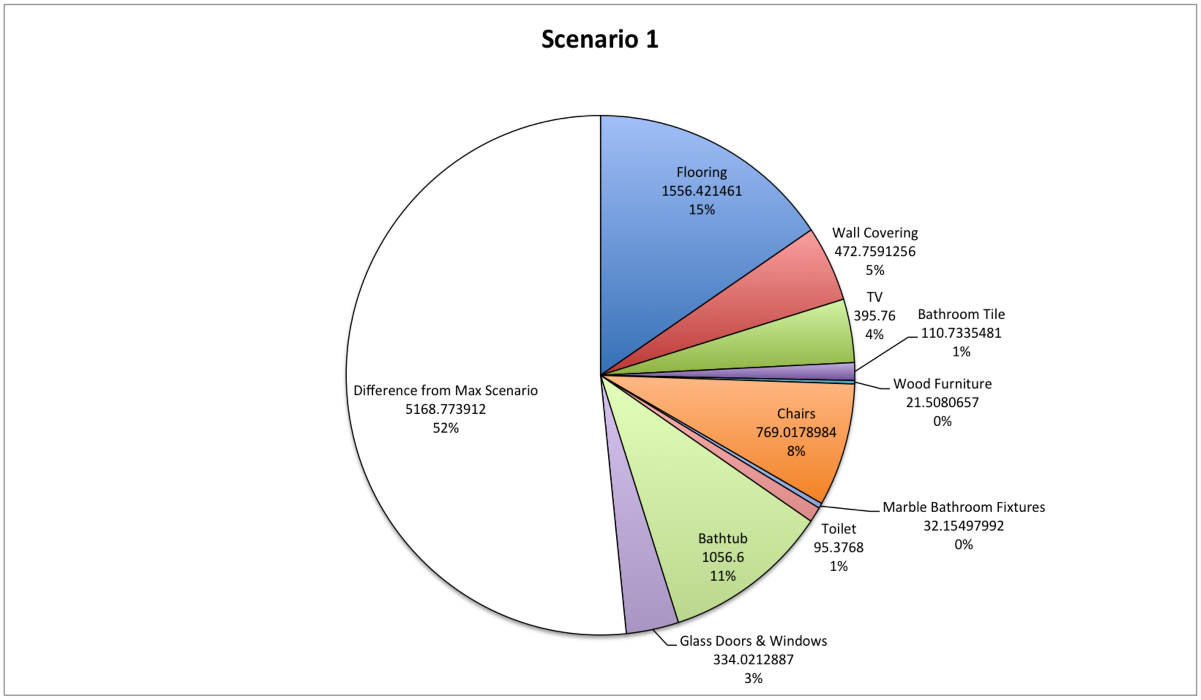
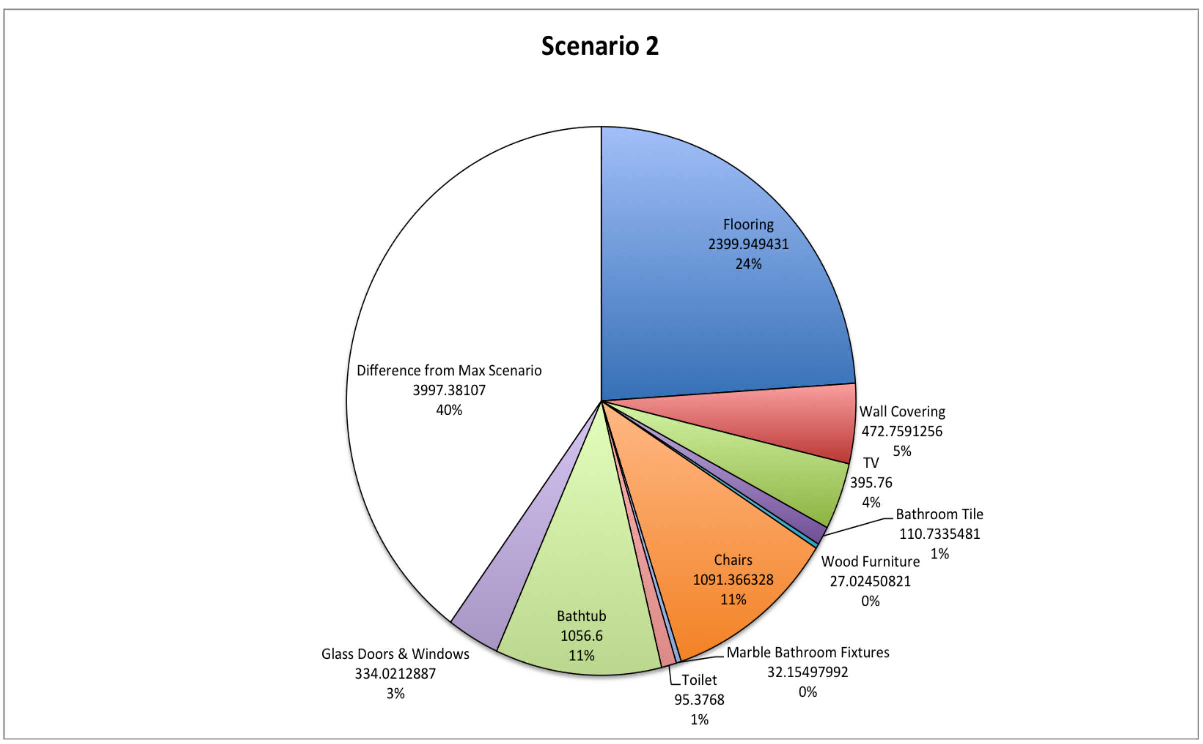


Figure 25. These pie charts are CO_2 data for the hotel scenarios. Each pie chart shows the percent contribution of each component for each scenario.

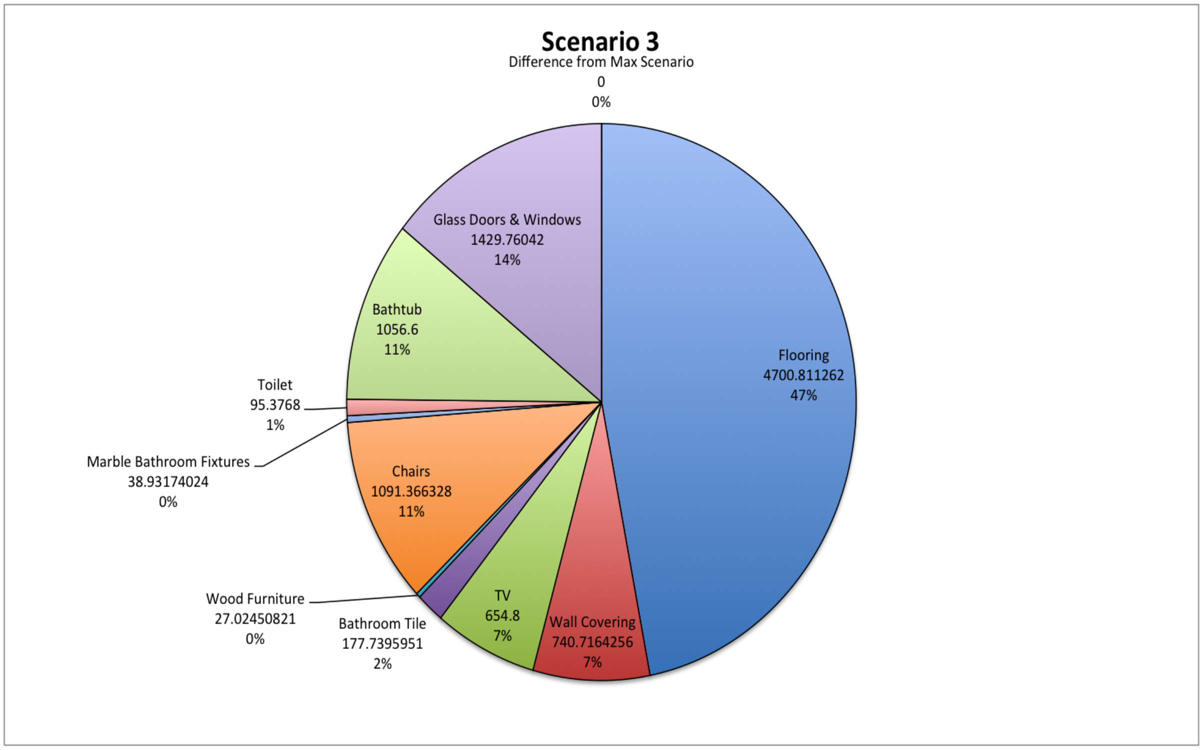
26 (A)


Scenario 1
Flooring
1556.421461
15%
Wall Covering
472.7591256
5%
TV
395.76
4%
Bathroom Tile
110.7335481
1%
Wood Furniture
21.5080657
0%
Chairs
769.0178984
8%
Marble Bathroom Fixtures
32.15497992
0%
Toilet
95.3768
1%
Bathtub
1056.6
11%
Glass Doors & Windows
334.0212887
3%
Difference from Max Scenario
5168.773912
52%

26 (B)

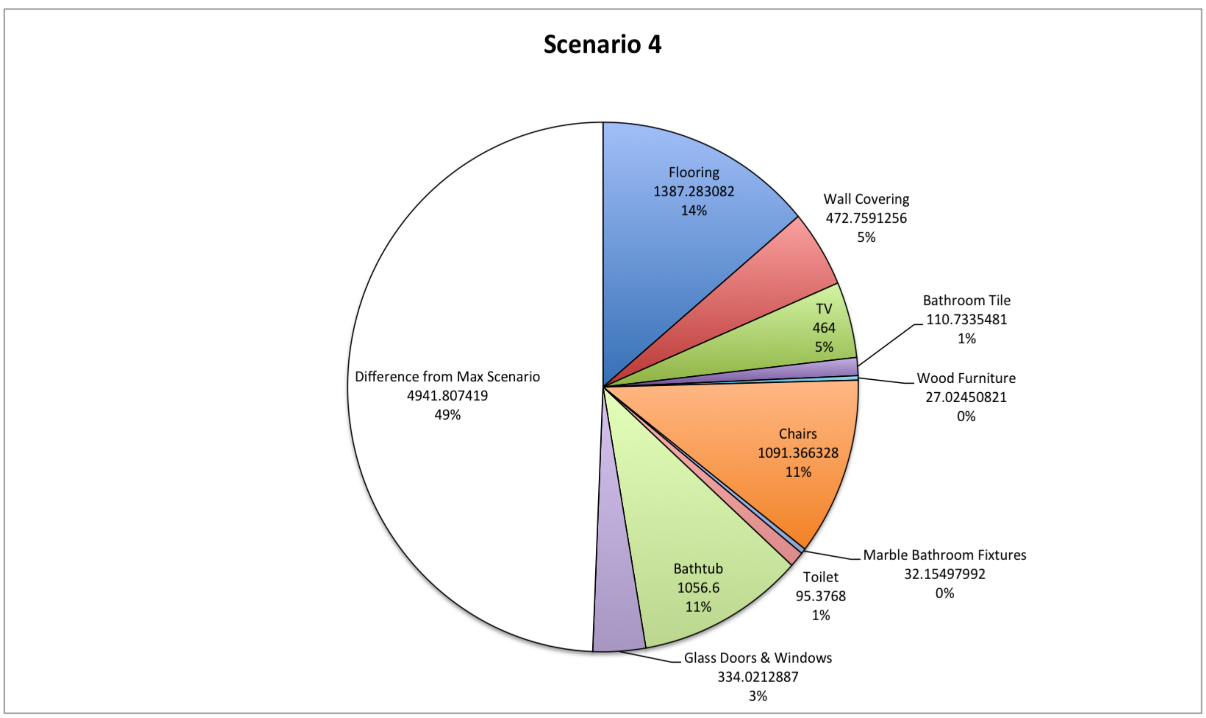

Scenario 2
Flooring
2399.949431
24%
Wall Covering
472.7591256
5%
TV
395.76
4%
Bathroom Tile
110.7335481
1%
Wood Furniture
27.02450821
0%
Chairs
1091.366328
11%
Marble Bathroom Fixtures
32.15497992
0%
Toilet
95.3768
1%
Bathtub
1056.6
11%
Glass Doors & Windows
334.0212887
3%
Difference from Max Scenario
3997.38107
40%

26 (C)



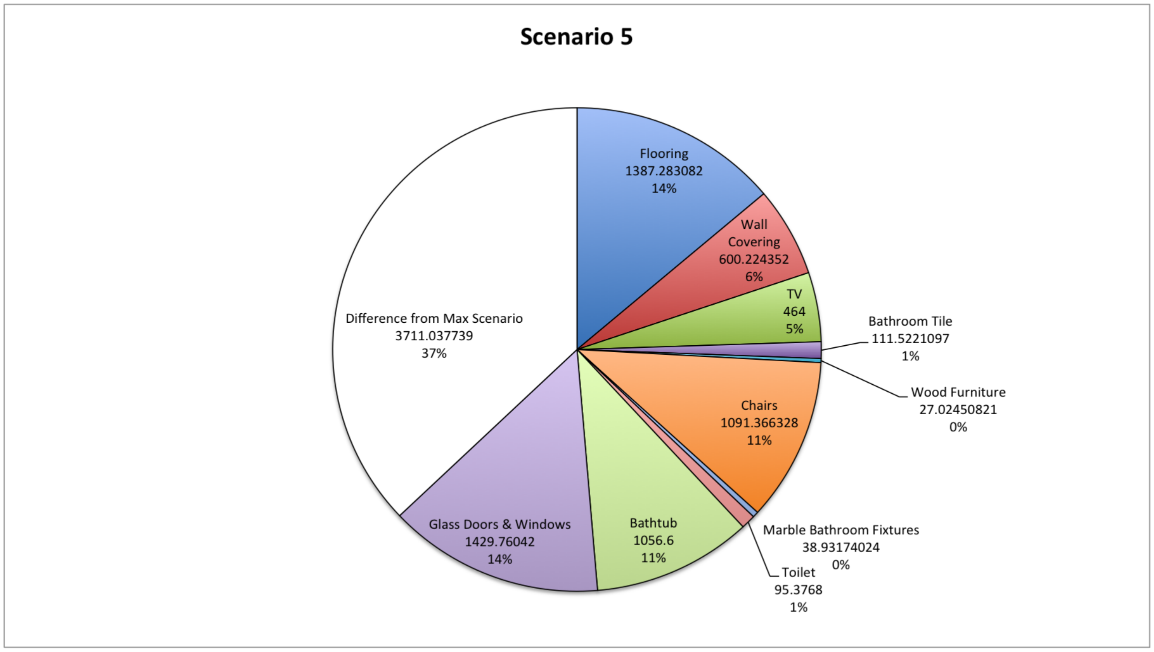
Scenario 3
Difference from Max Scenario
0
0%
Glass Doors & Windows
1429.76042
14%
Flooring
4700.811262
47%
Bathtub
1056.6
11%
Toilet
95.3768
1%
Marble Bathroom Fixtures
38.93174024
0%
Chairs
1091.366328
11%
Wood Furniture
27.02450821
0%
Bathroom Tile
177.7395951
2%
TV
654.8
7%
Wall Covering
740.7164256
7%

26 (D)



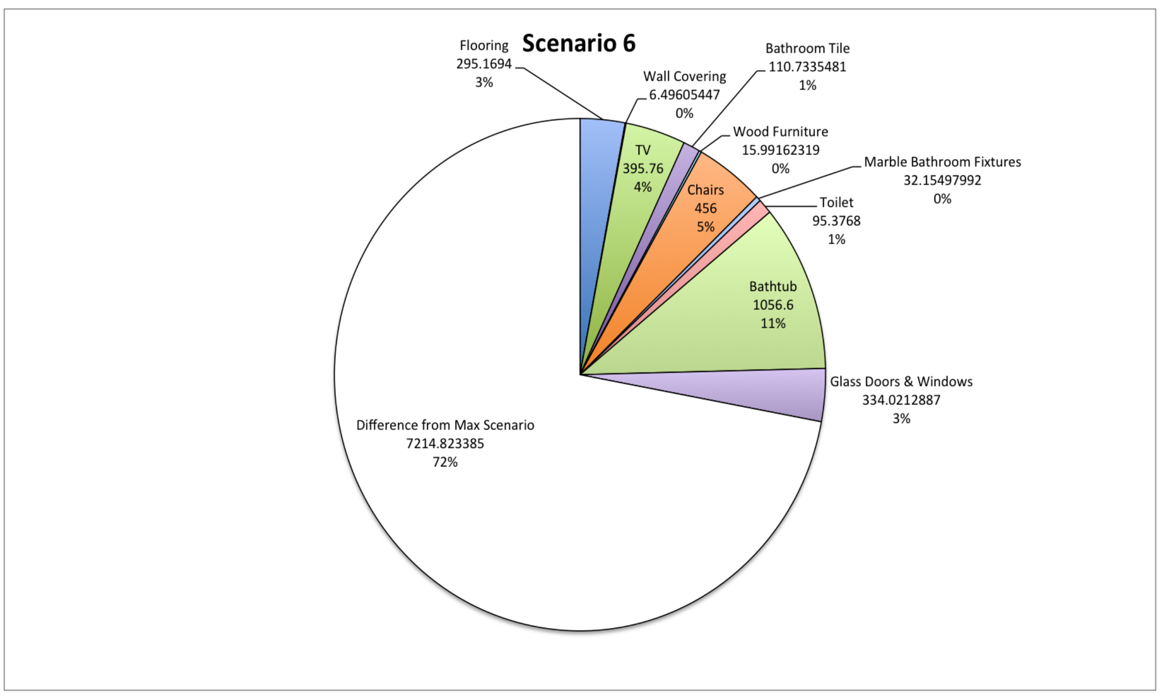
Scenario 4
Flooring
1387.283082
14%
Wall Covering
472.7591256
5%
TV
464
5%
Bathroom Tile
110.7335481
1%
Wood Furniture
27.02450821
0%
Difference from Max Scenario
4941.807419
49%
Chairs
1091.366328
11%
Marble Bathroom Fixtures
32.15497992
0%
Toilet
95.3768
1%
Bathtub
1056.6
11%
Glass Doors & Windows
334.0212887
3%

26 (E)



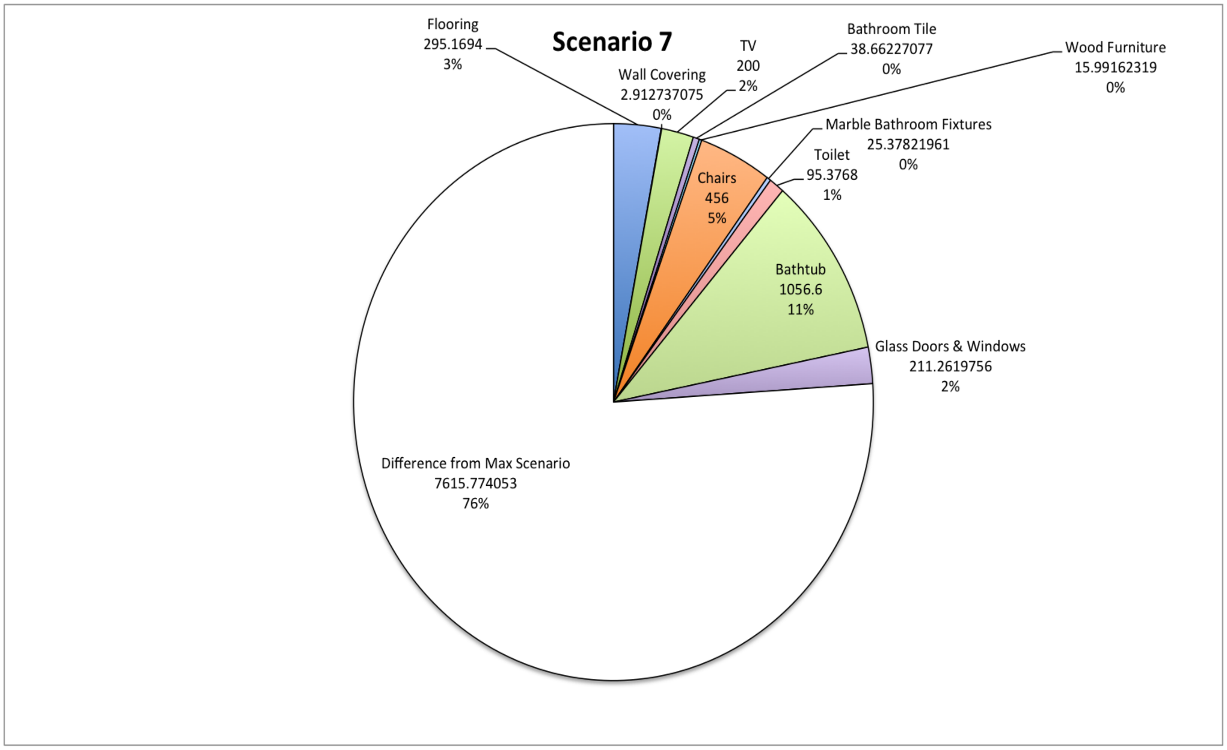
Scenario 5
Flooring
1387.283082
14%
Wall Covering
600.224352
6%
TV
464
5%
Bathroom Tile
111.5221097
1%
Wood Furniture
27.02450821
0%
Chairs
1091.366328
11%
Marble Bathroom Fixtures
38.93174024
0%
Toilet
95.3768
1%
Bathtub
1056.6
11%
Glass Doors & Windows
1429.76042
14%
Difference from Max Scenario
3711.037739
37%

26 (F)

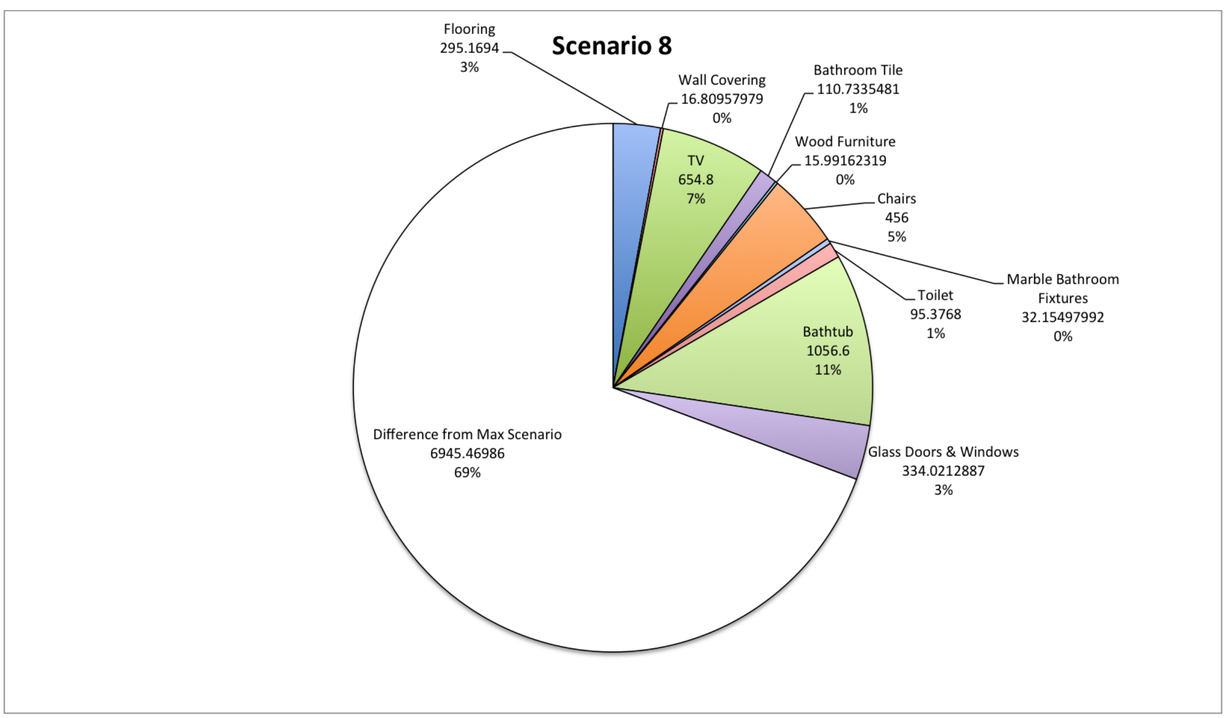


Scenario 6
Flooring
295.1694
3%
Wall Covering
6.49605447
0%
Bathroom Tile
110.7335481
1%
Wood Furniture
15.99162319
0%
Marble Bathroom Fixtures
32.15497992
0%
TV
395.76
4%
Chairs
456
5%
Toilet
95.3768
1%
Bathtub
1056.6
11%
Glass Doors & Windows
334.0212887
3%
Difference from Max Scenario
7214.823385
72%

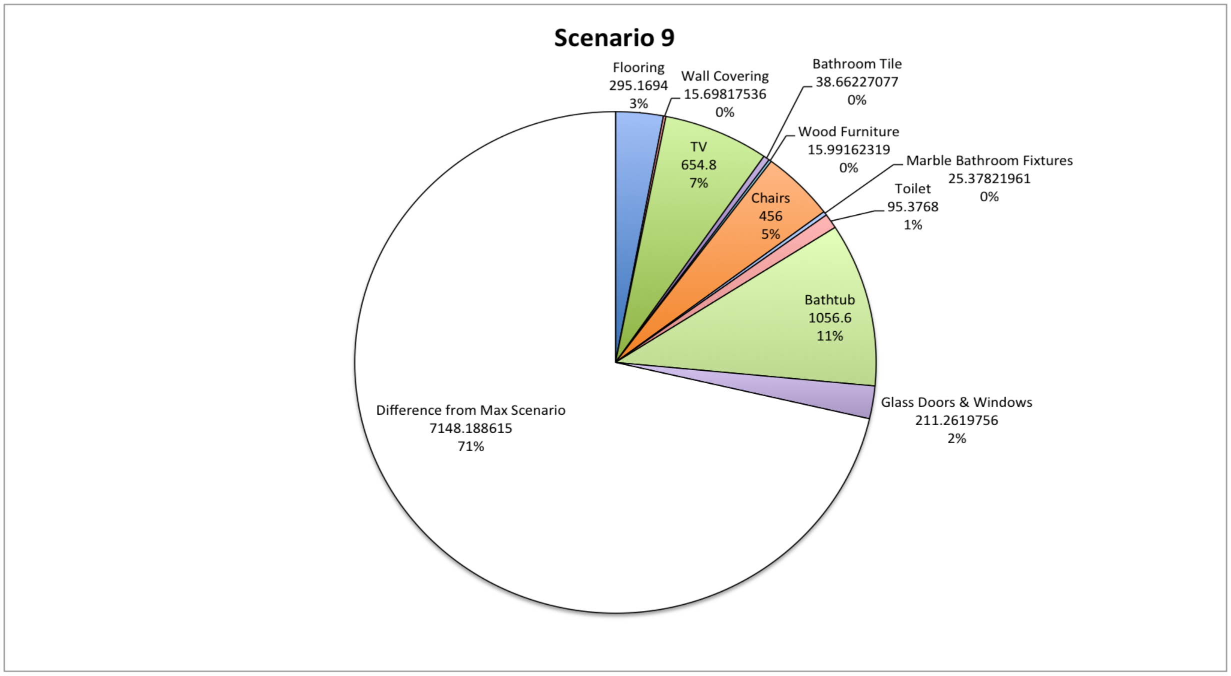
26 (G)


Scenario 7
Flooring
295.1694
3%
Wall Covering
2.912737075
0%
TV
200
2%
Bathroom Tile
38.66227077
0%
Wood Furniture
15.99162319
0%
Marble Bathroom Fixtures
25.37821961
0%
Chairs
456
5%
Toilet
95.3768
1%
Bathtub
1056.6
11%
Glass Doors & Windows
211.2619756
2%
Difference from Max Scenario
7615.774053
76%

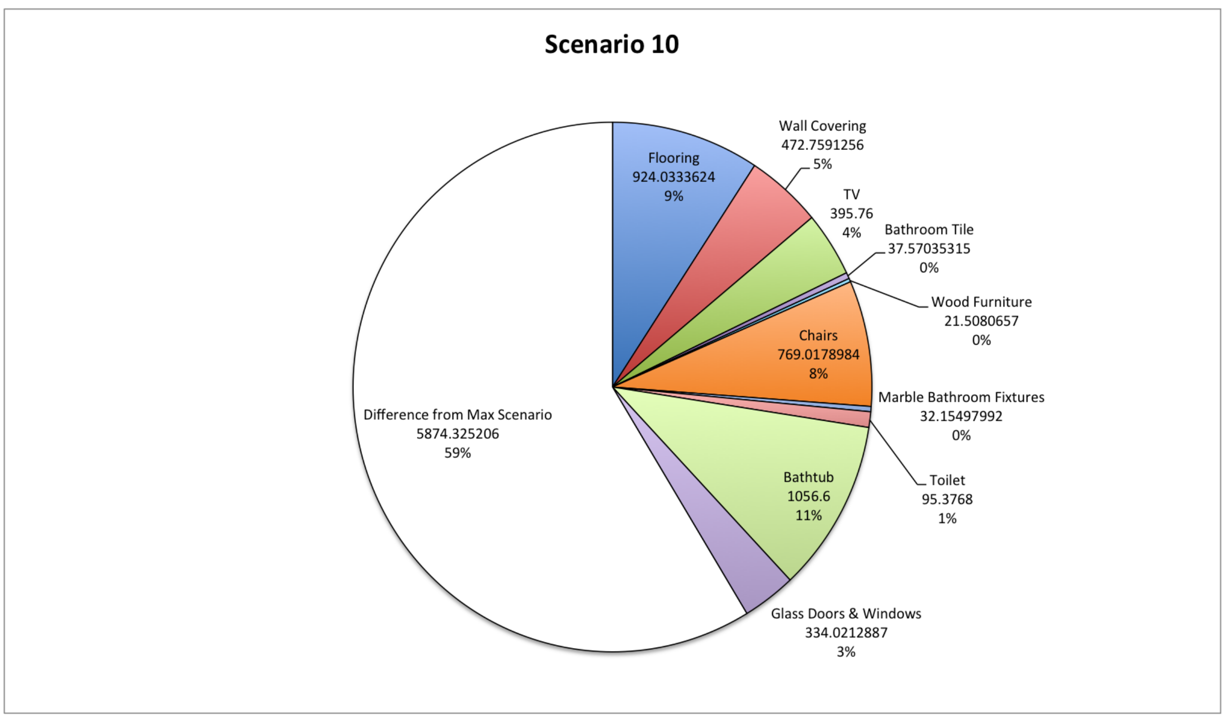
26 (H)


Scenario 8
Flooring
295.1694
3%
Wall Covering
16.80957979
0%
Bathroom Tile
110.7335481
1%
TV
654.8
7%
Wood Furniture
15.99162319
0%
Chairs
456
5%
Marble Bathroom Fixtures
32.15497992
0%
Toilet
95.3768
1%
Bathtub
1056.6
11%
Glass Doors & Windows
334.0212887
3%
Difference from Max Scenario
6945.46986
69%

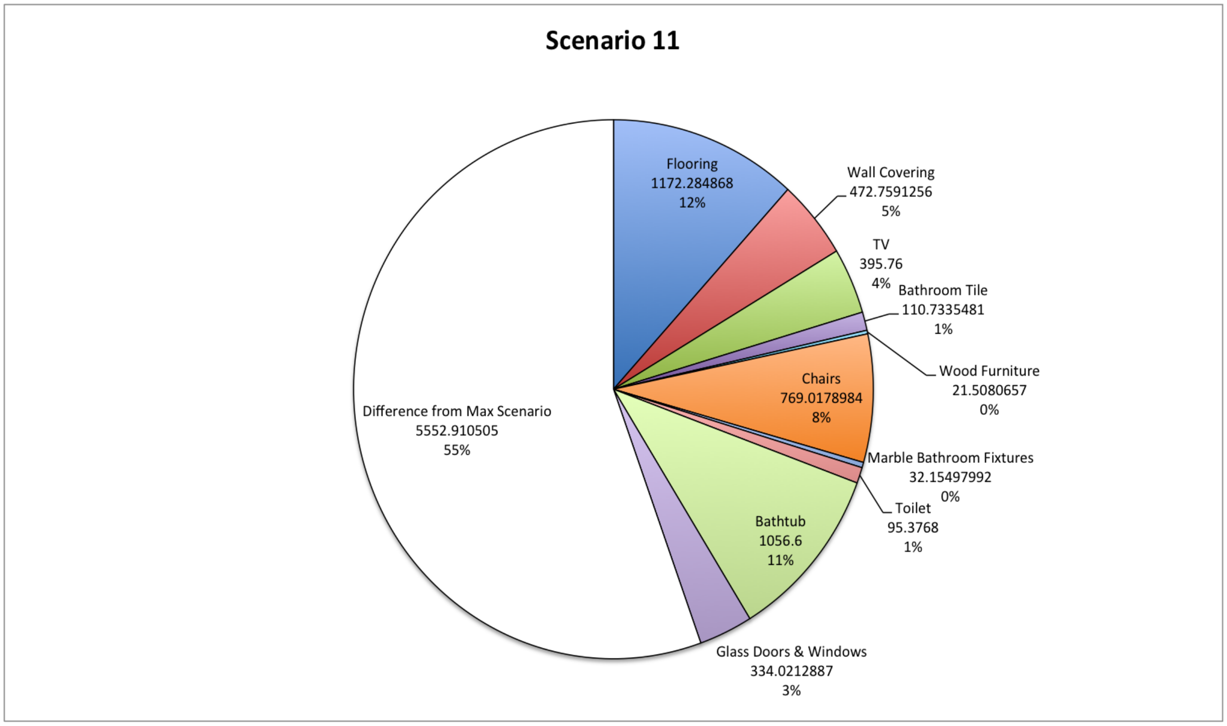
26 (I)


Scenario 9
Flooring
295.1694
3%
Wall Covering
15.69817536
0%
Bathroom Tile
38.66227077
0%
Wood Furniture
15.99162319
0%
Marble Bathroom Fixtures
25.37821961
0%
Toilet
95.3768
1%
TV
654.8
7%
Chairs
456
5%
Bathtub
1056.6
11%
Glass Doors & Windows
211.2619756
2%
Difference from Max Scenario
7148.188615
71%

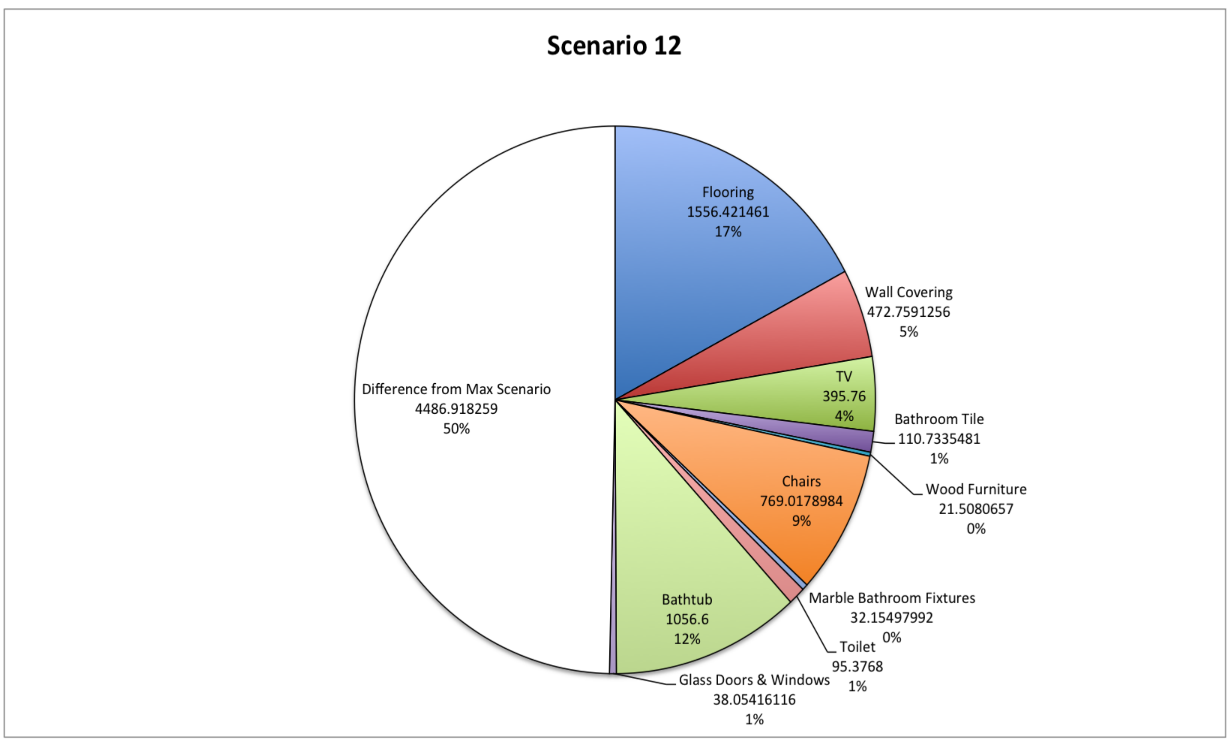
26 (J)


Scenario 10
Flooring
924.0333624
9%
Wall Covering
472.7591256
5%
TV
395.76
4%
Bathroom Tile
37.57035315
0%
Wood Furniture
21.5080657
0%
Chairs
769.0178984
8%
Marble Bathroom Fixtures
32.15497992
0%
Toilet
95.3768
1%
Bathtub
1056.6
11%
Glass Doors & Windows
334.0212887
3%
Difference from Max Scenario
5874.325206
59%

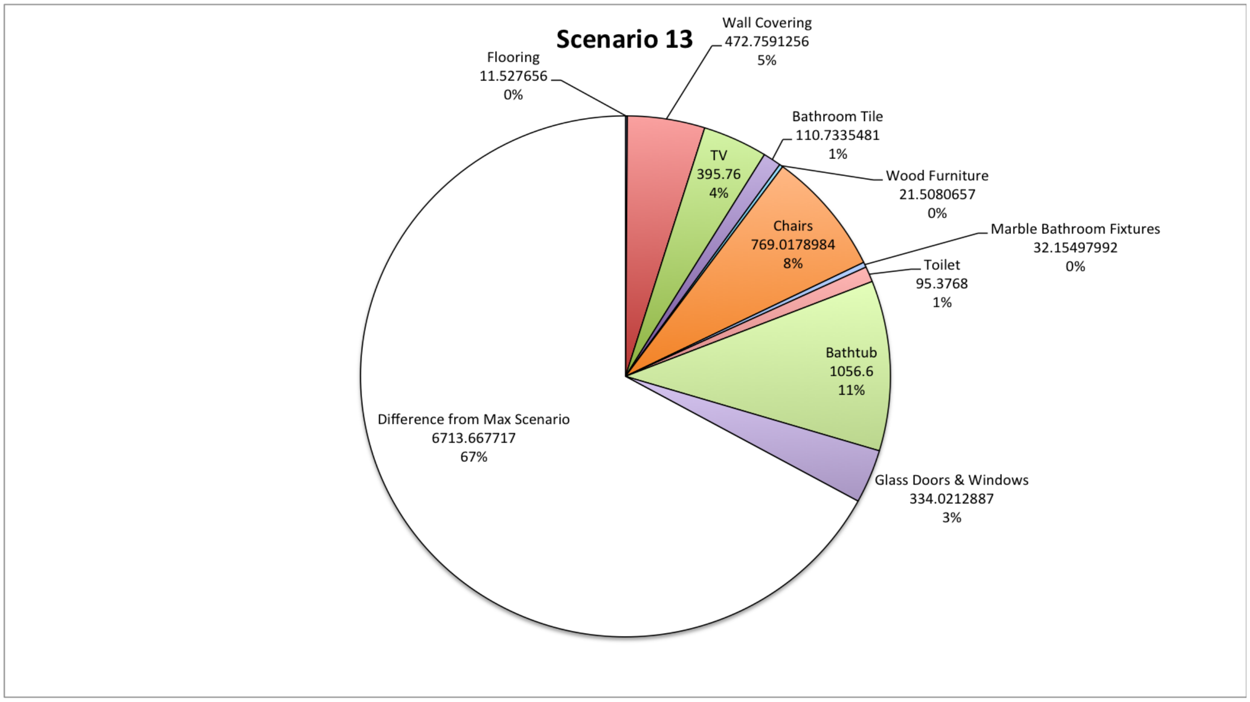
26 (K)


Scenario 11
Flooring
1172.284868
12%
Wall Covering
472.7591256
5%
TV
395.76
4%
Bathroom Tile
110.7335481
1%
Wood Furniture
21.5080657
0%
Chairs
769.0178984
8%
Marble Bathroom Fixtures
32.15497992
0%
Toilet
95.3768
1%
Bathtub
1056.6
11%
Glass Doors & Windows
334.0212887
3%
Difference from Max Scenario
5552.910505
55%

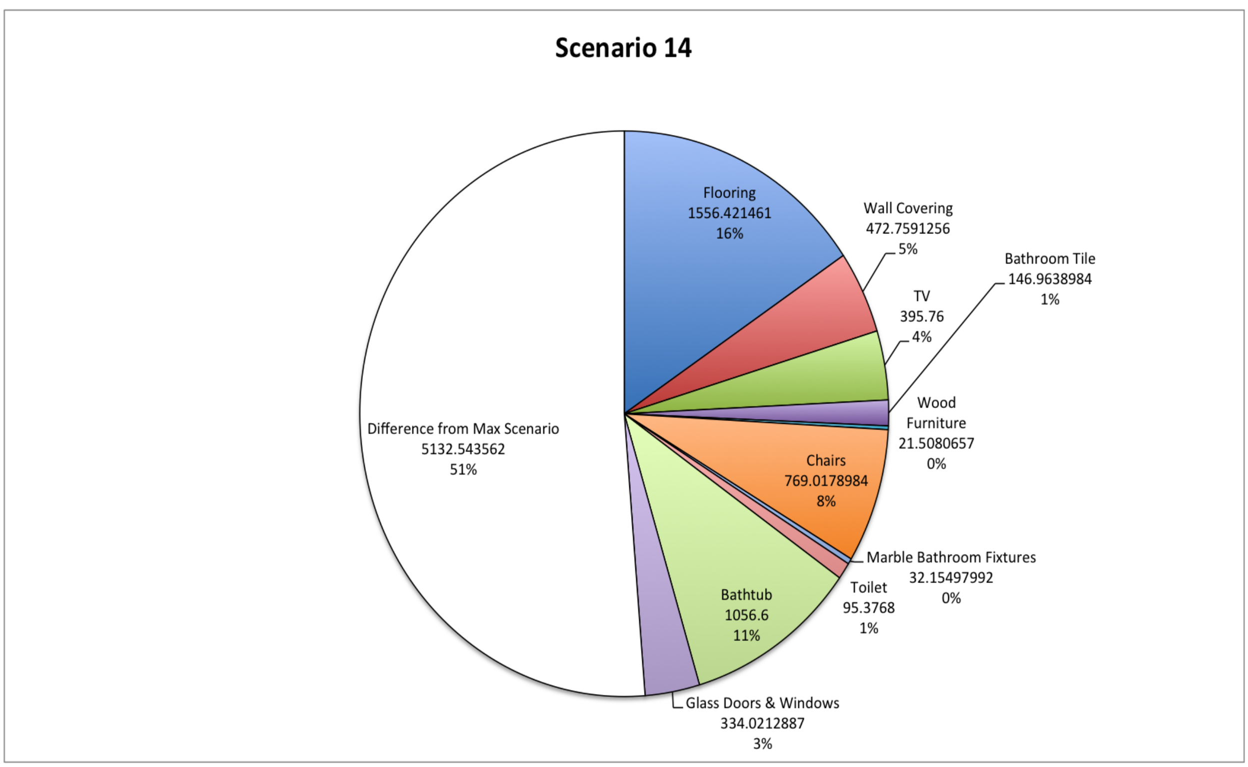
26 (L)


Scenario 12
Flooring
1556.421461
17%
Wall Covering
472.7591256
5%
TV
395.76
4%
Bathroom Tile
110.7335481
1%
Wood Furniture
21.5080657
0%
Chairs
769.0178984
9%
Marble Bathroom Fixtures
32.15497992
0%
Toilet
95.3768
1%
Bathtub
1056.6
12%
Glass Doors & Windows
38.05416116
1%
Difference from Max Scenario
4486.918259
50%

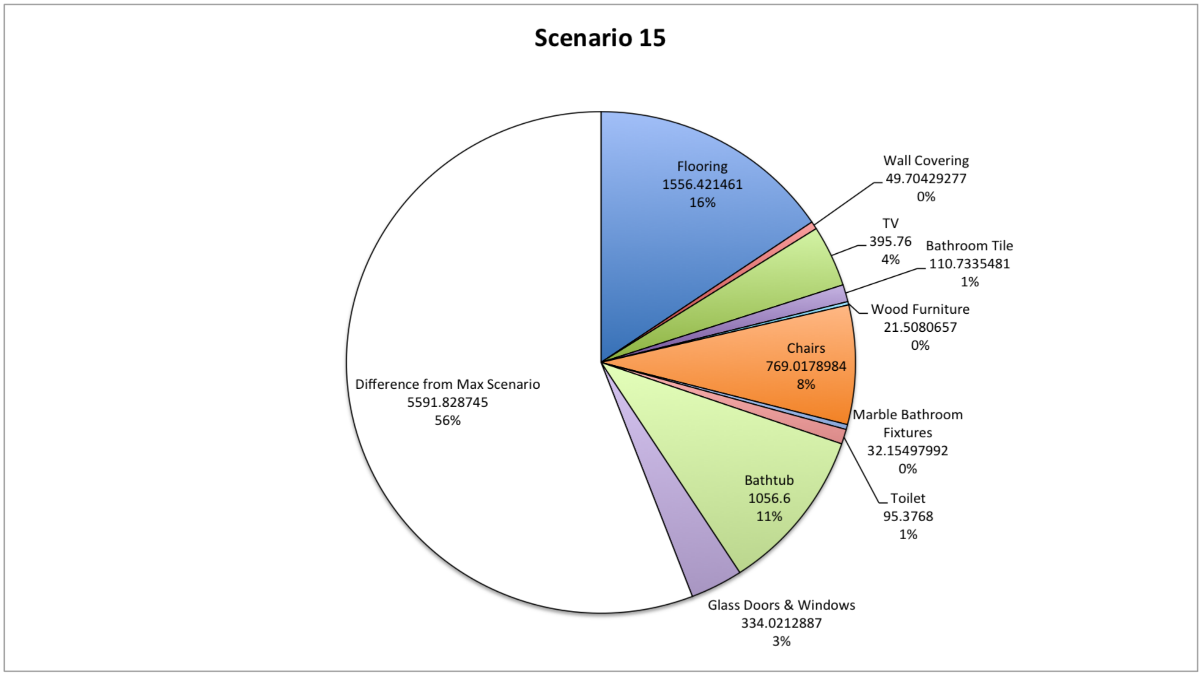
26 (M)


Scenario 13
Flooring
11.527656
0%
Wall Covering
472.7591256
5%
Bathroom Tile
110.7335481
1%
TV
395.76
4%
Wood Furniture
21.5080657
0%
Chairs
769.0178984
8%
Marble Bathroom Fixtures
32.15497992
0%
Toilet
95.3768
1%
Bathtub
1056.6
11%
Difference from Max Scenario
6713.667717
67%
Glass Doors & Windows
334.0212887
3%

26 (N)


Scenario 14
Flooring
1556.421461
16%
Wall Covering
472.7591256
5%
Bathroom Tile
146.9638984
1%
TV
395.76
4%
Wood
Furniture
21.5080657
0%
Difference from Max Scenario
5132.543562
51%
Chairs
769.0178984
8%
Marble Bathroom Fixtures
32.15497992
0%
Toilet
95.3768
1%
Bathtub
1056.6
11%
Glass Doors & Windows
334.0212887
3%

26 (O)



26 (P)

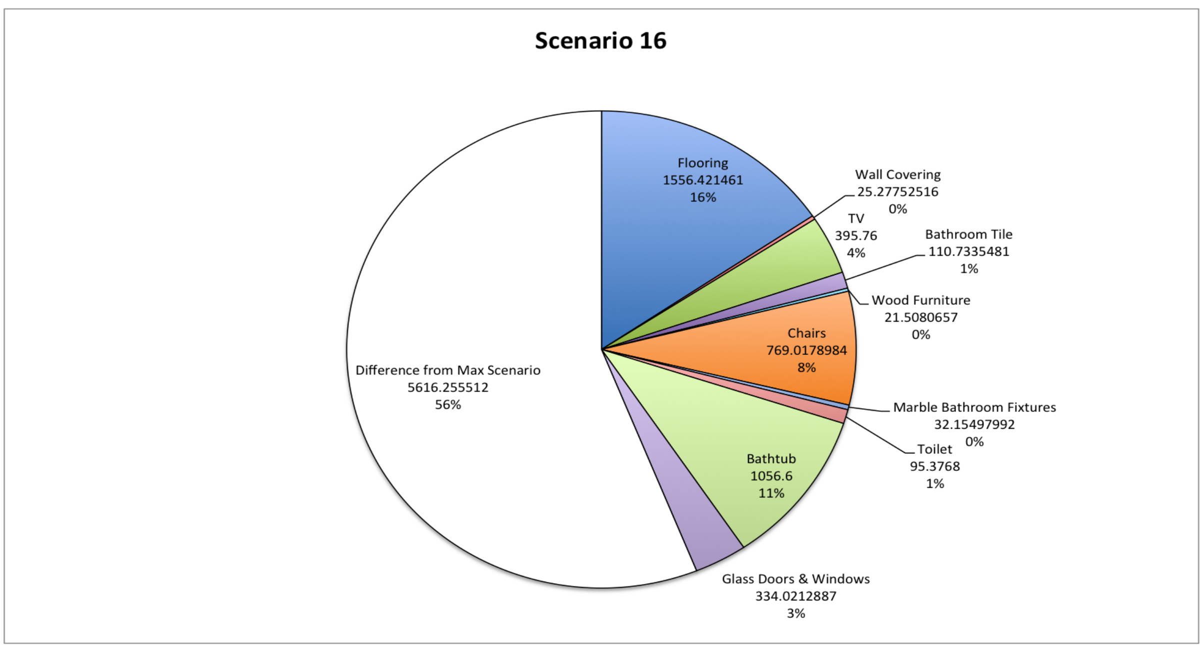


Figure 26. These pie charts show the difference between each scenario and scenario 3 (worst case scenario) shown in white. The rest of the colors represent the contribution from each component for the scenario.