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A Comparison of Rainwater Harvesting Tank Sizing Methods: Optimizing to Reduce Greenhouse Gas Emissions versus Maximizing System Reliability

by

Henry Rodriguez

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the

Master of Science Degree in

Civil Engineering

Dr. Defne Apul, Committee Chair

Dr. Ashok Kumar, Committee Member

Dr. Richard Becker, Committee Member

Dr. Amanda Bryant-Friedrich, Dean
College of Graduate Studies

The University of Toledo

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An Abstract of

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Rainwater Harvesting is a water conservation practice with a long history of implementation. With the advent of public water supply systems, they have become less common in developed areas of the world but there has been a resurgence as people struggle to find ways to minimize our ever-increasing impact on our environment. One of the most important consideration in rainwater harvesting systems is the sizing of the tank that stores water for later consumption. With increasing tank size, more rainwater can be stored reducing the need for potable water in dual piping systems and reduced emissions from potable water, but with increasing tank size there is more tank material and greater emissions for tank material. The purpose of this study is to determine if there are existing building configuration where attempting to minimize the Global Warming Potential emissions (Maximize Sustainability method) from the system will result in lower emissions than sizing the system by maximizing system reliability (Max VR method). Simulations were conducted with @risk using both sizing approaches for five different building types a small, medium, and large office, an apartment and a house. The results demonstrate that all building scenarios show a reduction in CO2 emissions with the

Maximize Sustainability method compared to BAU except for the house case. The Maximize Sustainability method produced lower CO_2 emissions in all cases compared to the Maximize VR method confirming that sizing with the Maximize Sustainability method does result in improved emissions for the different building configurations.

I dedicate this thesis to my wife Jessica. Her love throughout our time together has inspired me to work hard to achieve my goals and to follow my dreams no matter how big they may be.

Acknowledgements

I would like to thank Dr. Apul for being my research advisor. She provided timely feedback, technical support, and guidance on the work that resulted in this thesis. I would like to thank Jay Devkota for providing assistance in understanding Rainwater Harvesting LCAs and the components of a Rainwater Harvesting system. I would also like to thank Kelly Davis for summarizing data on the various building types that are used for the building cases in the simulations.

Lastly, but most importantly I would like to thank my wife Jessica who provided me with love and support throughout my entire time working on my Masters Degree. She took on more responsibilities than she should have and helped me focus when I couldn't. I really couldn't have done it without her.

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List of Abbreviations

BAU ....Business As Usual

CDF.............................Cumulative Distribution Function

GWP............................Global Warming Potential

LCA.............................Life Cycle Assessment

RWH ....Rainwater Harvesting

YAS.............................Yield After Spillage
YBS.............................Yield Before Spillage

List of Symbols

A................................Roof Area
C................................Runoff Coefficient
D................................Water Demand
E_{PW}.............................Emissions Potable Water
E_S................................Total Emissions
E_T ....Emissions Tank
H_T...............................Height of tank
M_{PW} ....Mass of potable water
M_T ....Tank material mass
P ....Depth of Precipitation
R_T ....Radius of Tank
S ....Supply from collected rainwater
T ....Tank capacity
T_T ....Tank thickness
UE_{PW} ....Unit Emissions Potable Water
UE_{TM} ....Unit Emissions Tank Material
V ....Volume of water in the tank
VR ....Volumetric reliability
Y ....Yield from the tank

ρ_m ....Tank material density

Chapter 1

Introduction

1.1 Background

The capture of rainwater for use as a water resource for various applications such as irrigation, washing, and for human consumptions has been practiced among many cultures across time. While Rainwater Harvesting (RWH) has a long history of implementation it has seen a resurgence in the modern era as people struggle to find ways to minimize our ever increasing impact on our environment.

RWH provides free water which can be used for irrigation and domestic water needs that do not require plumbing such as washing clothes and flushing toilets. RWH lessens the burden of both stormwater conveyance systems by storing stormwater and releasing it back into the system at a slower rate. Combined sewer systems benefit from this release lag as the likelihood of combined sewer overflow into a surface water is reduced.

Given these benefits communities have been pushing to find ways to push citizens and industry to implement RWH. One approach is to emphasize the economic benefits gained by the practice. The literature has many examples of economic analysis done on the implementation and maintenance of RWH system (Domènech & Saurí, 2011, etc.; Ghisi & de Oliveira, 2007; Hatibu, Mutabazi, Senkondo, & Msangi, 2006; Roebuck & Ashley, 2007; Wong, Tay, Wong, Ong, & Sia, 2003; Yuan, Fengmin, & Puhai, 2003). There are also many examples of the environmental analysis of RWH systems (Anand & Apul, 2011; Angrill et al., 2012; Devkota, Schlachter, Anand, Phillips, & Apul, 2013; Ghimire, Johnston, Ingwersen, & Hawkins, 2014; Morales-Pinzón, Lurueña, Rieradevall, Gasol, & Gabarrell, 2012; Ward, Butler, & Memon, 2012). These environmental analyses generally utilize Life Cycle Assessment (LCA) methodology. LCA provides a quantitative assessment of a process's environmental burdens based on the burdens associated with individual material and processes that are utilized or carried out throughout its life cycle.

Little work has been done on optimizing tank size for RWH systems based on the environmental metrics that result from LCA. In addition to the potential economic benefits obtained from RWH through water savings, RWH has the potential to reduce the environmental burdens that a building's operations incur. The storage tank component of a RWH system produces a large amount of the environmental impacts associated with the system. The storage tank also has the most flexibility in design, as it can be theoretically sized to capture the desired amount of runoff to supplement or replace a buildings water needs, within the constraint of the precipitation in the area and amount of space available for tank placement. However, there are both economic and environmental tradeoffs associated with tanks size. The environmental tradeoff with a greater tank size is that although more rainwater can be captured and used, reducing environmental burdens associated with potable water, the larger tank size will require more material and it will take more energy to transfer the materials to the site. Conversely, with a smaller tank less material and energy are associated with the tank however the amount of runoff that can be captured is reduced, thus increasing the potable water and its associated burdens. As a result of these tradeoff there should theoretically exist a tank size for each site where these tradeoffs balanced such that environmental burdens are minimized. If this environmental minimum is not smaller than the business as usual (BAU) case, RWH is not the best fit for the site if positive environmental benefits from system implementation are desired. This environmental minimum may or may not coincide with the economic minimum for the same system. However, if this environmental minimum reduces the environmental burden of a building it should be considered in system design assuming that it is not too far from the economic minimum.

The purpose of this investigation is to determine under which conditions, if any, does a lower Global Warming Potential (GWP) result when sizing a RWH storage tank to minimize GWP rather than sizing in the traditional way of maximizing system reliability. My hypothesis is that there are certain building types that will be sensitive to the sizing methodology and will result in lower emissions with the proposed method. If this is the case, my proposal is that this would prove as a better method of sizing the RWH system, as the primary reason that RWH systems are considered is to reduce impacts on the environment. They generally are not the only source of available water where they are implemented so the need for a system that maximizes volumetric reliability is not crucial.

To accomplish this goal, the resulting environmental performance of these case studies with regard to their volumetric reliability was studied for five types of buildings, in order to determine if the optimal volumetric reliability coincided with the maximum volumetric reliability for the building configuration or if it occurred a lower volumetric reliability in which case sizing the system with the proposed methodology would reduce GWP. The five building cases studied were a small, medium, and large office, an apartment and a house.

There are some studies in the literature with similar goals and approaches. Sample and Liu (Sample & Liu, 2014) performed a study on the optimization of tank volumes in regards to cost. The results from RASP, a rainwater harvesting model developed in MATLAB, were compiled in a spreadsheet. Results from the model were interpolated based on tank volume using a cubic spline algorithm implemented in VBA to determine the search space for the optimization. The search space was searched with the program Evolver developed by Palisade Corporation using the program's Optquest solver which utilizes several optimization techniques including scatter search integer programming, and neural networks to maximize the cost benefits of the system which include avoidance of stormwater utility fees, reduction in sewer charges, and water supply savings. The study was conducted on various use cases; however, the researchers were not able to find any cases with positive economic benefits.

While optimization based on cost benefits is obtained with this study, environmental benefits are not looked at. However, a similar approach could be taken in regard to tank optimization using the same approach. With the goal of the study in mind several models for permutations of tank shape, tank material, occupancy, and catchment area can be developed. An optimization algorithm can be used to search within a range of tank volumes to determine the optimum tank volume with regards to the environmental metrics. This can be done to build a set of data which can then be correlated with their volumetric reliabilities.

Morales-Pinzon et al. (Morales-Pinzón, Rieradevall, Gasol, & Gabarrell, 2015) developed a software program Plugrisost that could conduct economic and quantitative environmental analysis of a rainwater harvesting installation, while accounting for various parameters considered in the design of a rainwater harvesting system, most notably the sizing of the tank based on varying rainfall patterns. The researchers use this software along with simulated rainfall to optimize tank sizes for economic and the environmental indicator of Global Warming Potential (GWP). A systems dynamics approach is used to simulate the operation of the tank based on the supply to the tank and the water demand. The authors argue that the system dynamics approach can give conservative results regardless of the time interval when compared to the common behavior models Yield After Spillage (YAS) and Yield Before Spillage (YBS), as the model simulation of the tank level is instantaneous.

This simulation was conducted with GWP as the environmental indicator similar to the present study. However, the software is not open source so it is not easily customizable to accommodate developing simulation need. Their study results are not easily generalized to other rainfall and building characteristics as they are specific to the buildings and climate analyzed. It can be argued that simulation on such a fine scale is unnecessary as rainfall events are sporadic in nature. Researchers have found that daily simulations to be adequate in simulating rainwater harvesting performance (Fewkes, 2000; Mitchell, 2007).

Chapter 2

Methods

2.1 Rainwater Harvesting Model

The rainwater harvesting model in this study uses the YAS approach in modelling the behavior of the volume of rainwater in the tank. The YAS models the rainwater harvesting system by assuming that any yield from the collection supply will overflow from the tank before it is used by the system to meet the water demand. It is regarded as a more conservative method than the YBS approach which assumes this water is used by the system (Fewkes, 2000). The equations governing it are:

Equation 1: Yield at time t

$$Y_t = Min(D_t, V_{t-1} + S_t)$$

Equation 2: Volume in tank at time t

$$V_t = Min(V_{t-1} + S_t - Y_t, T - Y_t)$$

Where Y is the yield from the tank that is used to meet the demand of the system, D is the demand, V is the volume in the tank, S is the supply from the collected rainwater, and T is the tank capacity. Supply is based on Equation 3:

Equation 3: Supply at time t

$$S_t = A \cdot C \cdot P$$

Where A is the catchment area or roof area in this case, C is the runoff coefficient, and P is the depth of precipitation.

The demand is based off the occupancy of the building. A proportion of male to female is assumed for office buildings (50% male, 50% female). Men are assumed to use a urinal twice a day and the toilet once a day. Women are assumed to use the toilet three times a day (Vickers, 2001, pp. 27,77). Values of 1.6 gallons per flush are used for toilets and 1.0 gallons per flush for urinals. For residential cases people are assumed to use toilets for their bathroom needs. A 5.5 day week is used for the simulations of the office cases, 7 days for residential cases. The system lifetime, over which total emissions for the different cases are compared, is 75 years.

Volumetric reliability (VR) of a rainwater harvesting system is the ratio of the rainwater yield of the system and the demand of the system. It is a measure of how much of the system demand is met by the rainwater captured by the rainwater harvesting system. The usual method of sizing tanks for RWH applications is to maximize this parameter so that as much of the demand as possible is provided by captured rainwater. If the total available rainwater supply is less than the demand of the system this will result in values less than one. The minimize GWP emissions system sizing method considered in this investigation, referred to as the Maximize Sustainability method hereafter for brevity, will not always result in the maximum possible volumetric reliability. A comparison of this metric between the two methods thus demonstrates the amount of downsizing of the system that is necessary to achieve minimal GWP emissions.

Equation 4 expresses this relationship where Y_i is the yield at time i, and D is the demand at time i. The Maximize VR method simulates the usual method of sizing the system by selecting the smallest tank size that will result in the highest possible VR given the supply of rainwater captured by the system and the given demand. This is done for each iteration of the simulation with a VBA Subroutine based on binary search. Further details on the solver are discussed in supplemental information.

Equation 4: Volumetric Reliability

$$VR = \frac{\sum_{i=1}^{T} Y_i}{\sum_{i=1}^{T} D_i}$$

Total emissions (E_S) are based on the sum of the emissions from potable water (E_{PW}) used and emissions from the tank material (E_T) (Equation 5). Potable water emissions are the product of the emissions rate for potable water and the mass of the potable water used by the system throughout its lifetime (Equation 6). The mass of potable water can be expressed in terms of VR and D_i, the demand at time i (Equation 7), which results in Equation 8. Similarly, tank emissions are the product of the emissions rate for the tank material and the mass of tank material (Equation 9). The tank is not replaced throughout the system lifetime.

Equation 5: Emissions System

$$E_S = E_{PW} + E_T$$

Equation 6: Emissions Potable Water

$$E_{PW} = \quad M_{PW} \cdot UE_{PW}$$

Equation 7: Emissions Potable Water

$$M_{PW} = \quad (1 - VR) \cdot \sum_{i=1}^{T} D_i$$

Equation 8: Emissions Potable Water

$$E_{PW} = \quad (1 - VR) \cdot \sum_{i=1}^{T} D_i \cdot \ UE_{PW}$$

Equation 9: Emissions Tank

$$E_T = \quad M_T \cdot UE_{TM}$$

Equation 10 gives the relationship used to determine the tank material mass, M_T, where T_T is the thickness of the tank material, R_T is the radius of the tank, H_T is the height of the tank, and ρ_m is the density of the tank material. Tank height is assumed to be 7.5 feet. The radius of the tank was found for a given volume with the assumed tank height with Equation 11.

Equation 10: Tank Material Mass

$$M_T = 2 \cdot \pi \cdot T_T \cdot (R_T^2 + R_T \cdot H_T) \cdot \rho_m$$

Equation 11: Radius of Tank

$$R_T = \sqrt{\frac{V}{H_T \pi}}$$

Equation 12 expresses the total emissions for the RWH system, E_S, in terms of VR, the unit emissions for potable water, UE_{PW}, the mass of tank material, M_T, and the unit emissions for the tank material, UE_{TM}. For the minimize emission case of the simulations this expression is minimized to obtain the tank size and volumetric reliability that will result in the lowest total CO_2 for the system life time of 75 years. Table 1.1 summarizes assumptions and parameters of the RWH model not varied during simulation.

Equation 12: Emissions of System

$$E_S = (1 - VR) \cdot \sum_{i=1}^{T} D_i \cdot UE_{PW} + M_T \cdot UE_{TM}$$

Emissions data used in these equations is based off unit emissions data obtained from ecoinvent based of the life cycle inventory chosen for the study, the tank and potable water emissions. This data is summarized in Table 1.2. Other parts of the rainwater system such as piping, gutters, pumps, and filters were not included as they were considered outside the scope of the study which is focused on the rainwater harvesting tank sizing. The functional unit is the provision of water for toilet flushing for a the modeled building for the lifetime of 75 years.

Table 2.1: RWH Model Assumptions and Parameters

	Commercial	Residential	Units
Tank Height	7.5	7.5	Feet
Tank Thickness	0.25	0.25	Inches
Potable Water Emissions	0.00031	0.00031	kg Co_2- Equiv/kg
Bathroom Usage	3	3	Times/day
Male/Female Ratio	50/50	-	-
Urinal Water Consumption	1.0	-	Gallons/flush
Toilet Water Consumption	1.6	1.6	Gallons/flush
System Life	75	75	Years
Days of Operation	5.5	7	Days

Table 2.2: Summary of emissions data

Component	GWP (kg CO2 eq/kg)
Potable Water	0.00031
Tank	2.5-6.5 (Uniform Distribution)

2.2 Monte Carlo Simulation

To accomplish the goals of the study, several system parameters that vary between rainwater harvesting system were assigned distributions and Monte Carlo simulations were run. Doing so in this way assures that a wide variety of systems are simulated, emulating their variability in real world applications.

Simulations were run with @Risk Excel add on for Microsoft Excel, marketed by Palisade Corporation. 10,000 iterations of the model were run, with Latin Hypercube sampling and the Mersenne Twister random number generator. The parameters varied in the simulations are summarized in Table 2.1. The people parameter has a normal distribution associated but decimals are rounded due to fractions of people not being realistic. Table 2.2 summarizes the statistical parameters of the distributions for the five different building cases. Statistical parameters for the distributions for the runoff coefficient and tank emissions remained the same for all the building case. The statistical parameters for the distributions for occupancy and roof area/people varied based on the simulation case. The four parameters that were varied were chosen because they are the parameters from the model that are most likely to vary, aside from rainfall, from building to building.

Rainfall is held constant for all simulations cases; rainfall depths are based off weekly totals collected by the Toledo Airport in 2014. The same rainfall depths are used over the 75 year lifetime of the RWH systems. This approach was taken to reduce the complexity of the model. However, this limits the rainfall portion of the model to this specific Toledo rainfall data. For this reason, a negative answer to our hypothesis does not necessarily rule out the possibility that there might be a GWP reduction from the sustainability method under a different rainfall pattern. Given the fact there is a large variability in supply due to the variability of other parameters that dictate supply, namely the runoff coefficient and the roof catchment area, we can have some confidence that the model does cover some of the variability that would result from a more thorough treatment of rainfall. Improvements can be made to the model which can incorporate more rainfall data or rainfall can be simulated to describe more general conditions.

Table 2.3: Parameters of rainwater harvesting system that were varied

Name(Units)	Description	Distribution
Runoff Coefficient	Portion of rainfall collected by the system	Uniform
Tank Emissions (kg-CO2 Equiv./kg)	Associated emissions with tank material	Uniform
People	Occupancy of the building	Normal
Roof Area/People (S.F./People)	Ratio of roof area to people, used to determine roof area.	Normal

Table 2.2: Statistical Parameters of distributions for the five building cases

Building Case	Runoff Coefficient		Tank Emissions (kg-CO2 Equiv./kg)		People		Roof Area/People (S.F./People)		Roof Area (S.F.)
	Min	Max	Min	Max	Mean	Standard Deviation	Mean	Standard Deviation	-
Small Office	0.65	0.98	2.5	6.5	28	7	196.5	49.1	5502
Medium Office	0.65	0.98	2.5	6.5	269	67.3	66.5	16.6	17876
Large Office	0.65	0.98	2.5	6.5	2493	623.3	16.7	4.2	41549
Apartment	0.65	0.98	2.5	6.5	88	22	95.9	24	8435
House	0.65	0.98	2.5	6.5	4	1	266.3	66.6	1065

The range for the Runoff Coefficient were obtained from a minimum 65% collection efficiency obtained from the Texas Rainwater Harvesting Manual (Krishna, 2005) to a theoretical high collection efficiency of 98% assuming an ideal collection surface. The tank emissions range was based on Ecoinvent data for ceramics emissions and pvc emissions. This range of numbers was used to reflect different materials used in rainwater harvesting tanks.

Five building cases were chosen for the study to determine in which scenarios the proposed sizing methodology is most appropriate if it all. These cases were a small, medium, and large commercial building (Small Office, Medium Office, and Large Office), a one-family residential home (House) and an apartment complex (Apartment). The reason these were chosen were due to the availability of the data and to have a comparison between a residential and commercial use cases of different sizes. The ranges for the occupancy and roof area/people parameters are shown in table 2.2. The ranges for the occupancy and the roof area/people were based from occupancy and roof area data in the United States from the Census Bureau and ASHRAE Energy Standards for commercial buildings (ASHRAE, 2004; Census_Bureau, 2015; Gowri, Halverson, & Richman, 2007) . The mean and standard deviations were based of the collected building data. The mean used was the mean from the available data while the standard deviation was assumed to be 25% of the mean, which was believed to be a conservative estimate necessitated by the limited data.

The Small Office has a mean roof area of 5502 SF roughly five times the roof area of House (1065 S.F.). Apartment has a mean roof area roughly eight time that of House (8435 SF) and a mean of 88 occupants compared to 4 for House. Medium and Large office have mean roof area of 17876 and 41549 and mean occupancy of 269 and 2493. This results in a decreasing Roof Area/People from Small to Large Office for the commercial cases, which is important in determining the Demand to Supply ratio of the building (higher Roof Area/People generally resulting in lower Demand to Supply ratios). Similarly, House has higher Roof Area/People than Apartment.

Roof area for the model was calculated by excel from occupancy and roof area/people, roof area being the product of these two parameters. Doing so in this way assures that iterations do not result in roof areas that are too small to support the occupants and conversely iterations do not result in a small number of occupants for a building with a very large roof area, since this ratio is kept within a realistic range by the roof area/people parameter.

The simulations were run with no tank to simulate the resulting emissions from the simulated buildings without RWH implemented, BAU, the RWH system with tank size sized with the proposed methodology of minimizing emissions, and the RWH system sized to maximize volumetric reliability, the present methodology used to size RWH systems tanks currently. The Excel solver was run from VBA during the simulations for each iteration for the last two cases to either minimize GWP emissions for the proposed methodology or to maximize volumetric reliability for the present sizing methodology.

10,000 iterations were chosen for each of the simulations. Figure 2-1 shows the overall modeling approach.

While the present study does utilize commercial software to preform Monte Carlo simulations of the optimization procedure, similar simulations can be programmed with Microsoft Visual Basic for Applications as the optimization utilizes Excels goal seek for optimization. However, there is a significant drop in simulation speed with this method.

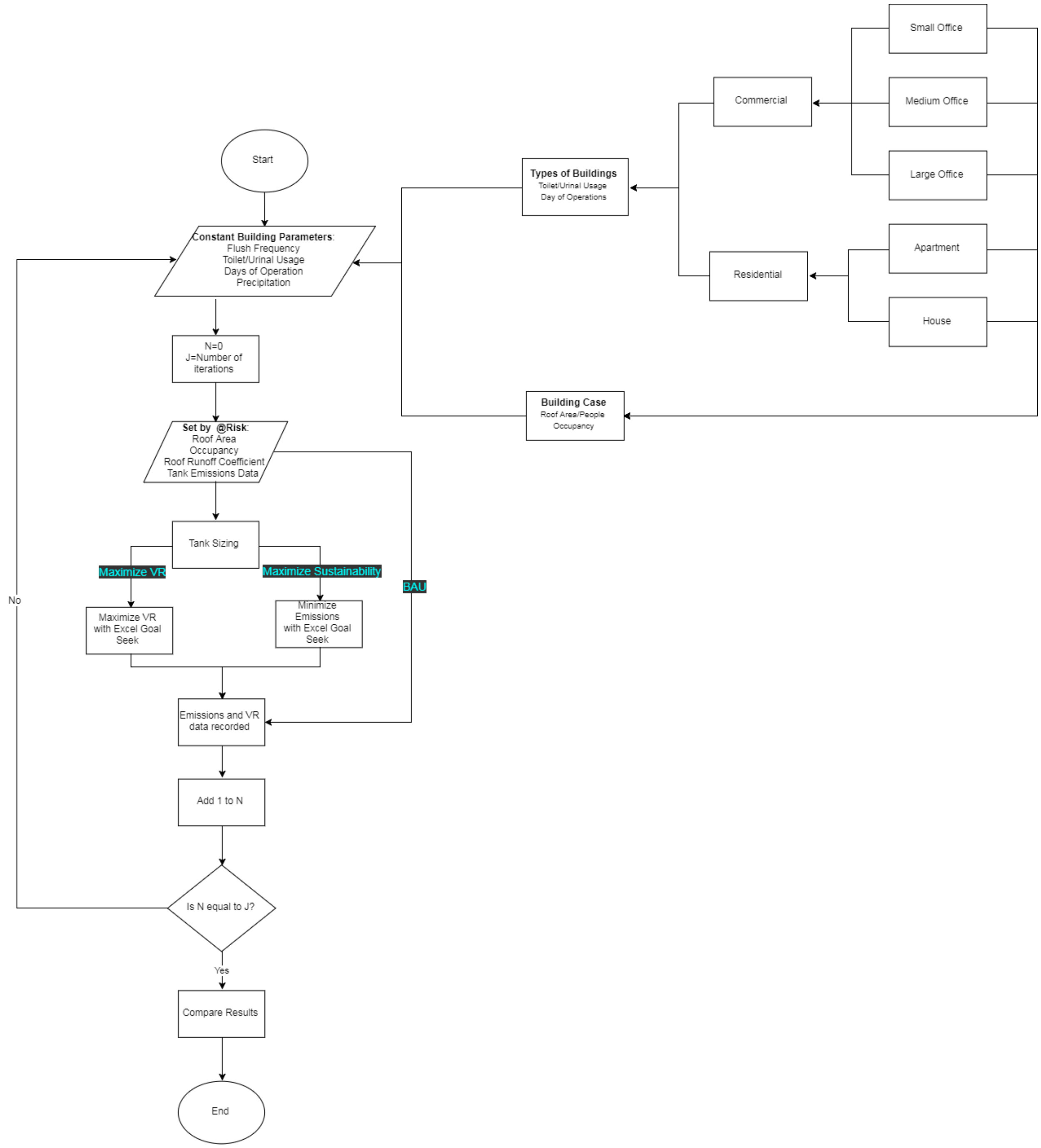


Figure 2-1: Schematic representation of modeling approach

Chapter 3

Results

3.1 Small Office

Figure 3-1a provides the CDFs of VR for the Maximize Sustainability and Maximize VR simulations. For Small Office, the median VR for the Maximize Sustainability method is 0.71 and 1.00 for the Maximize VR method. The 25th and 75th percentiles of VR for the Maximize VR method are higher than the Maximize Sustainability method, with an absolute difference of 0.35 and 0.24 respectively. A lower VR indicates that a lower amount of the building demands is supplied by the system. This indicates that the Maximize Sustainability method on average produces lower tank sizes than the Maximize VR method as tank size is the only parameter affected by the change in methodology. The shape of the CDF for Maximize Sustainability near-normal. The shape of the CDF for the Maximize VR is not normal, with a majority of the VRs for the simulation being close to 1. In fact, for the Maximize VR method the 1th percentile of VR for the simulation is 1, indicating that for this simulation case enough water can be captured by the system to meet the most demand in a large majority of iterations. However, without a comparison of the distribution of total emissions between the methods and the case of no tank where RWH is not implemented, BAU, we cannot be sure whether the Maximize Sustainability method results in lower emissions. Figure 1-b displays CDFs of total emissions for these three cases.

Figure 3-1b provides the CDFs of total emissions for the Maximize Sustainability method, BAU, and Maximize VR simulations. Comparing the median total emissions for the three different cases, the Maximize Sustainability method produces the lowest median total emissions, followed by the BAU case, and the Maximize VR method. This indicates that not only does the Maximize Sustainability method produce lower emissions on average than BAU, but also that sizing the tank to maximize the use of available rainwater, the Maximize VR method, results in greater emissions than BAU. The CDF of BAU and the sustainability appear to be normal. The CDF for the Maximize VR method has a heavier right tail indicating higher variability in emissions above the median, when compared to BAU and the sustainability method and a greater deviation in emissions from these cases as total emissions from the system increase. Between BAU and Maximize Sustainability, there is some overlap in the distribution of emissions at low percentiles, but consistent separation at higher percentiles. This indicates that the Maximize Sustainability method is consistently resulting in lower emissions when compared to BAU.

(a)

(b)

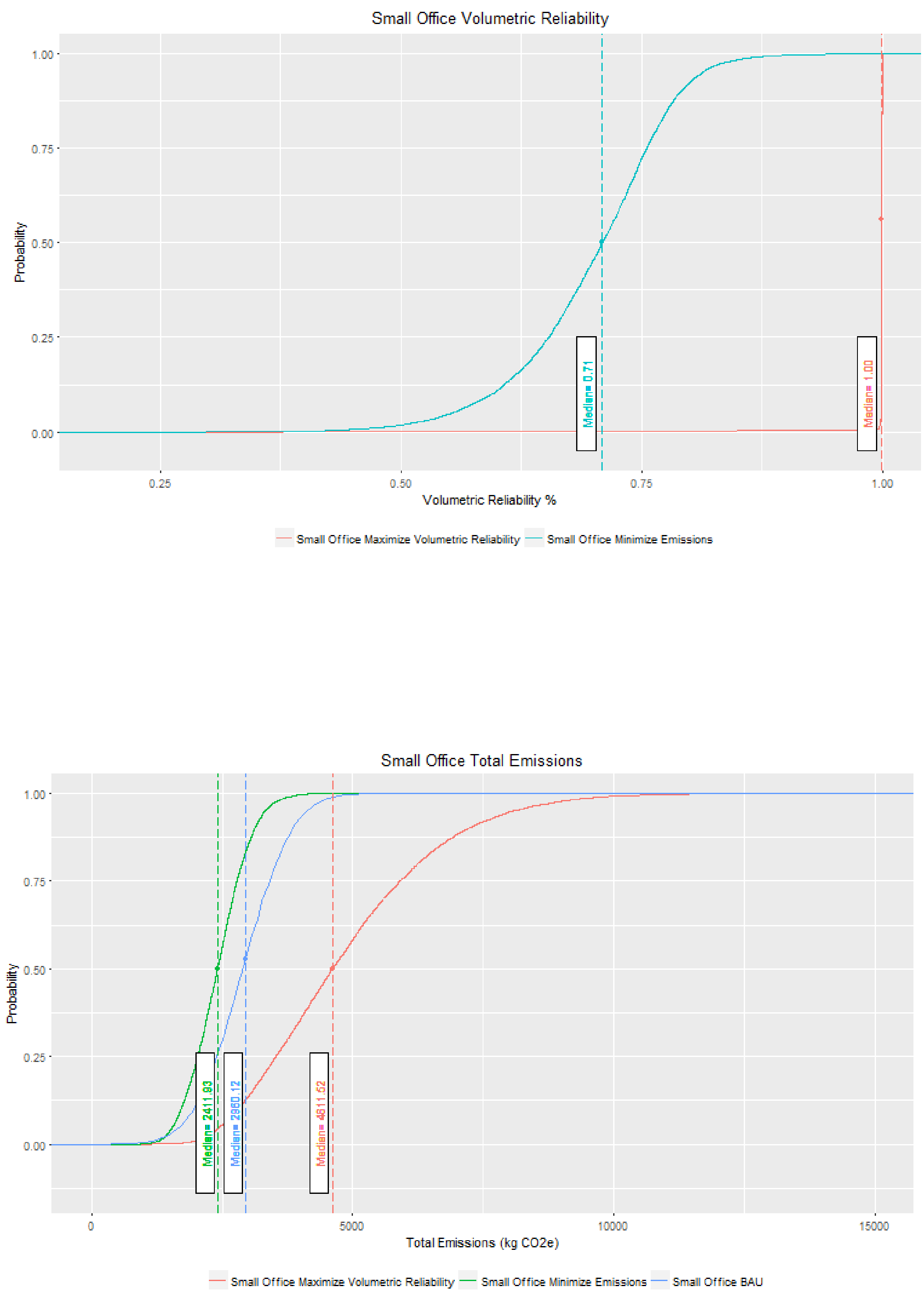


Figure 3-1: CDFs for Small Office Case: a) Volumetric reliability b) Total emission

3.2 Medium Office

Figure 3-2a provides the CDFs of VR for the Maximize Sustainability and Maximize VR simulations. For the medium school case, the median VR for the Maximize Sustainability method is 0.32 and 0.91 for the Maximize VR. Method. The reason for this is that the Maximize Sustainability method results in smaller tank sizes than the Maximize VR method. The absolute difference between the medians of VR between the two methods is greater for Medium Office (median difference = 0.59) than for Small Office (median difference = 0.29). The 25th and 75th percentiles of VR between the two methodologies also have a greater absolute difference in the Medium Office (difference in 25th and 75th percentile = 0.48) than in the Small Office (difference in 25th and 75th percentile = 0.44). The shapes of the VR CDFs are also different than in the Small Office case with both methodologies being non-normal. Also of note, there is a greater distribution of VR for the Maximize VR method than in the Small Office case. The difference between 25th percentile and 75th percentile for the Medium Office case for this scenario is 0.26 as opposed to 0 for the Small Office case. This is a result of their not being enough rainwater supply to meet the system demand in some of the iterations of the simulation for the Medium Office case.

Table 3.1: Median Demand to Supply Ratio for Simulation Cases

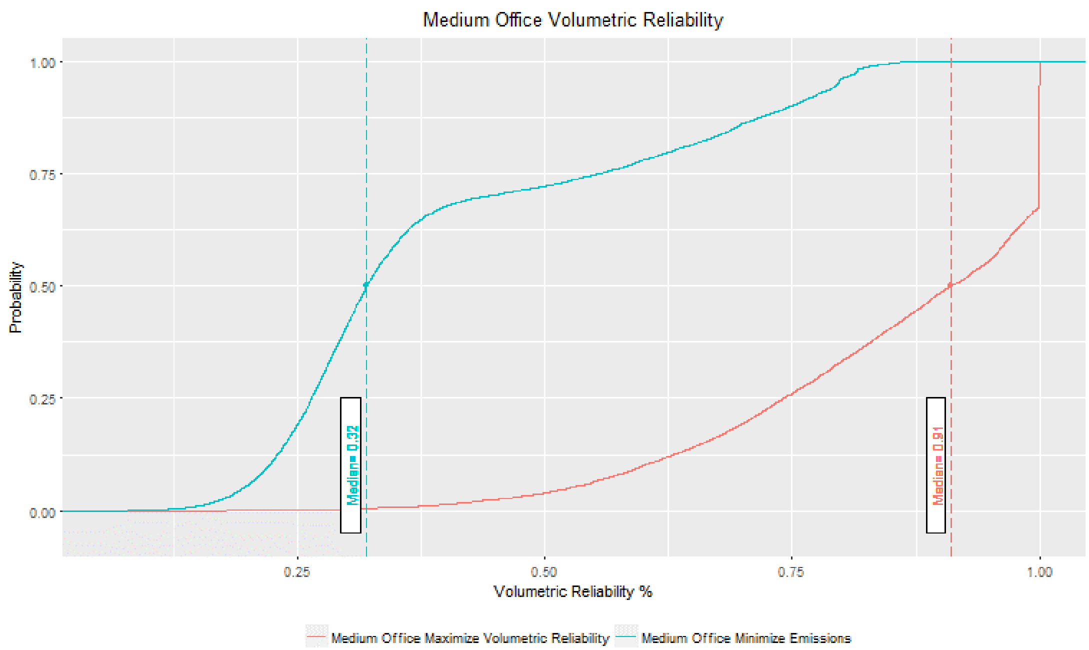
Simulation Case	**Median Demand To Supply Ratio**
Apartment BAU	1.1
Apartment Maximize VR	1.1
Apartment Minimize Emissions	1.1
House BAU	0.4
House Maximize VR	0.4
House Minimize Emission	0.4
Large Office BAU	4.3
Large Office Maximize VR	4.3
Large Office Minimize Emissions	4.3
Medium Office BAU	1.1
Medium Office Maximize VR	1.1
Medium Office Minimize Emissions	1.1
Small Office BAU	0.4
Small Office Maximize VR	0.4
Small Office Minimize Emissions	0.4

Table 3.1 which provides the median demand to supply ratios of all the simulation cases supports this. The values are calculated by dividing the annual demand by the annual supply. Demand to Supply ratios less than 1 indicate that the annual demand of a building is low enough to be fully supported by the annual rainfall supply to that building. Median demand to supply ratio for the Maximize VR scenario were 0.4 and 1.1 for Small Office and Medium Office respectively.

The value for the Medium Office case is close to 1, meaning the median annual demand and rainwater supply for the simulations are almost equivalent. This shows in the CDF shape leaning to VR values over 0.50. The Maximize Sustainability method CDF has a normal shape with a long right tail (the 75th percentile of VR is 0.55 and 95th percentile is 0.80) indicating some iterations which resulted in high VR. However, most iteration were below 0.55 (lower than the median for the Maximize VR method). It is apparent that the two methods result in significant differences in the sizing the sizing of the RWH system.

Figure 3-2b provides the CDFs of total emissions for the Maximize Sustainability, BAU, and Maximize VR. Comparing the median total emissions for the three different cases, the Maximize Sustainability method produces the smallest median total emissions, followed by BAU, and the Maximize VR method. The Maximize Sustainability method produces better emissions results than BAU. The Maximize VR method also produces lower emissions results than BAU. The shape of the CDFs for the Medium Office case are similar to Small Office. BAU and the Maximize Sustainability method are normal, Maximize VR is near-normal with a longer right tail. There is greater separation between Maximize Sustainability and BAU, while BAU is closer to Maximize VR then it was for Small Office. Differences in the 25th, median, and 75th percentile of total emissions between Maximize Sustainability and BAU expressed as a percentage of the median BAU total emissions are 23.04%, 26.92%, and 30.15% respectively for Medium Office and 13.04%, 18.52%, and 23.48% for Small Office meaning that the separation of Maximize Sustainability and BAU emissions are consistently higher than in Small Office. The 25th percentile difference for Medium Office is close to the 75th percentile difference for Small Office, which could indicate some degree of overlap between the smaller building iterations of Medium Office and the larger building iterations of Small Office.

(a)



(b)

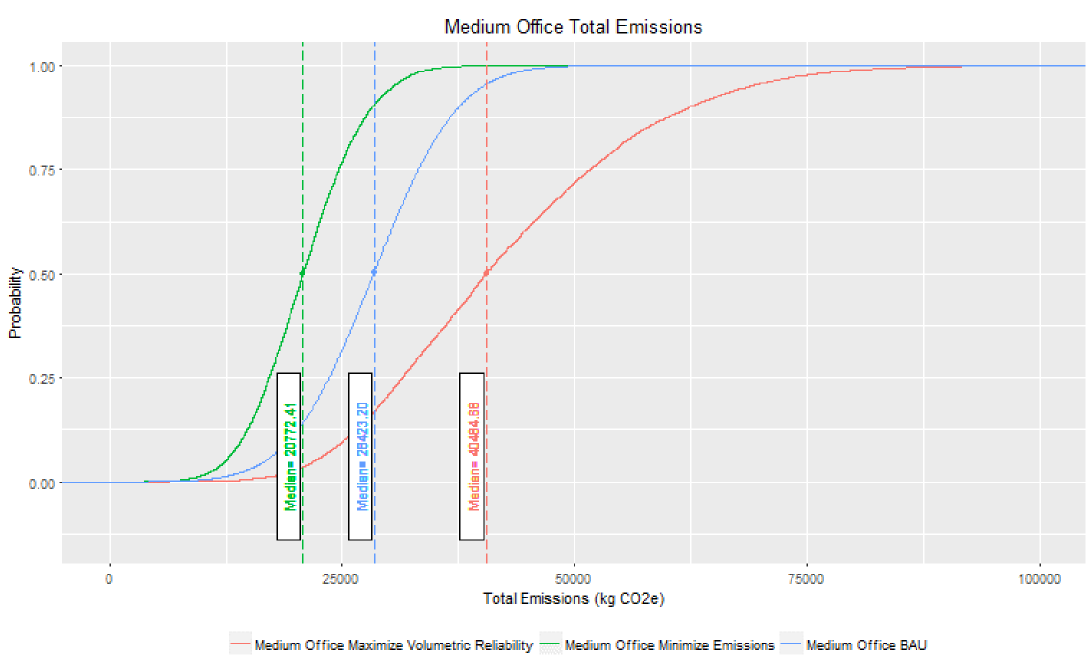


Figure 3-2: CDFs for Medium Office Case: a) Volumetric reliability b) Total emission

3.3 Large Office

Figure 3-3a provides the CDFs of VR for the Maximize Sustainability and Maximize VR methods. The median VR for Maximize Sustainability and Maximize VR is 0.15 and 0.23 respectively. As in previous cases the Maximize Sustainability method results in a lower median VR. However, the difference in median VR between the methods is 0.07, as opposed to 0.59 for Medium Office and 0.29 for Small Office. Similar comparisons can be made for the 25th and 75th percentiles with Large Office having a difference in VR between methods of 0.11 and 0.08, 0.48 and 0.44 for Medium Office and 0.35 and 0.25 for Small Office. Large Office has smaller reductions in VR with the Maximize Sustainability method compared to Small Office and Medium Office. Medium office has the largest reduction in VR between methods.

Looking at the demand to supply ratios of the three office cases from Table 3.1, Large Office has a demand to supply ratio of 4.3 indicating that the rainwater supply is only adequate to address less than a quarter of the system demand. Medium office has a demand to supply ratio slightly greater than 1 at 1.1, almost enough rainwater supply to meet the full system demand and Small Office had a demand to supply ratio of 0.4, more than enough rainwater supply to meet the demand. The small difference in VR between methods for Large Office could be a result of the low supply available for Large Office.

Figure 3-3b provides the CDFs of total emissions for Maximize Sustainability, BAU, and Maximize VR. Comparing the median total emissions for the three different cases, the Maximize Sustainability method produces the lowest emissions, followed by BAU, and Maximize VR. All three CDF curves are normal. The Maximize VR CDF does not have the long left tail exhibited in the other cases. This can be an effect of the tank emissions constituting a smaller portion of the total overall emission reducing the impact of iterations for Large Office where the tank emissions parameter is large. There is less separation between BAU and minimize sustainability than in the previous cases.

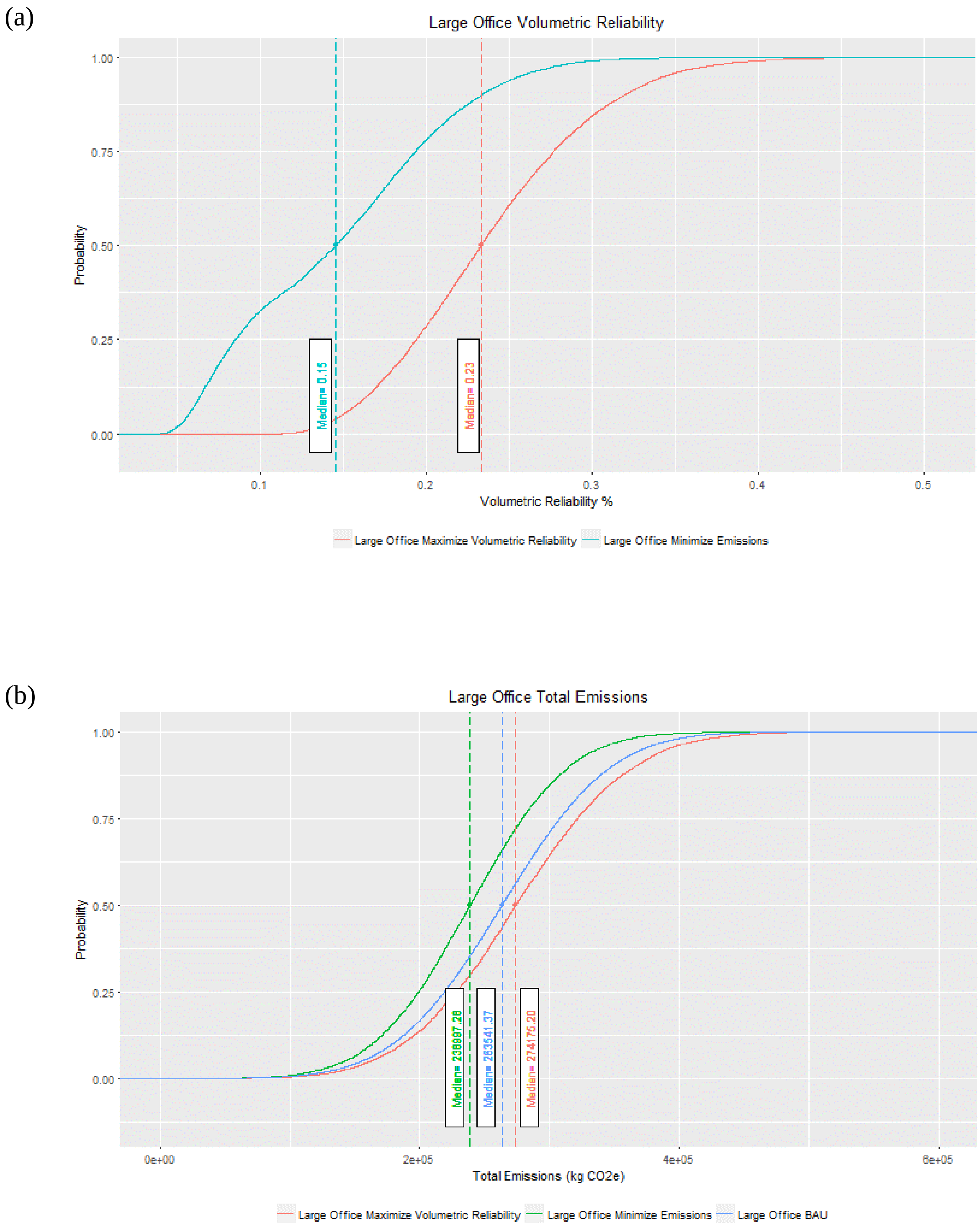


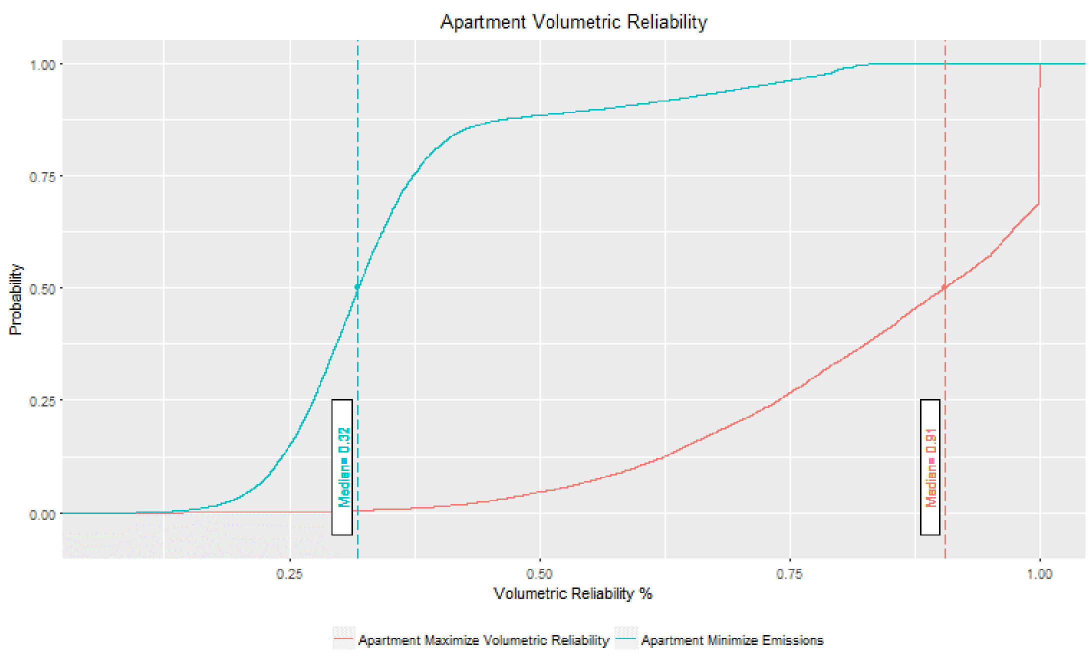
Figure 3-3: CDFs for Large Office Case: a) Volumetric reliability b) Total emission

3.4 Apartment

Figure 3-4a provides the CDFs of VR for the Maximize Sustainability and Maximize VR methods. For Apartment, the median VR for Maximize Sustainability and Maximize VR is 0.32 and 0.91 respectively. Maximize sustainability produces a lower median volumetric reliability during the simulations. The medians for the two methods are identical to Medium Office, which could result from their identical median demand to supply ratio. The 25th and 75th percentiles of VR between the two methods are 0.46 and 0.63 respectively. The difference in the 25th percentile between methods is 0.48 similar to Medium Office. The difference in the 75th percentile is greater than Medium Office. Despite the similarity in the median VR between Medium Office and Apartment the results are not identical. The 25th percentile of the two methods is similar to Medium Office. The 75th percentile for Maximize VR is also similar between Medium Office and Apartment. Looking at the 75th percentile of Maximize Sustainability the reason for the difference in separation between the two cases becomes apparent. The 75th percentile of VR for Maximize Sustainability is 0.55 and 0.37 for Medium Office and the Apartment case respectively. Comparing figures 3-2a and 3-4a one can see that the distributions for Maximize Sustainability follow a similar pattern with long right tails, but the right tail for Apartment is less pronounced meaning that the Maximize Sustainability method is resulting in smaller tank sizes in the higher demand iterations compared to Medium Office. The shape of the VR distributions between Apartment and Medium Office are nearly identical for the Maximize VR method so this only occurs with the Maximize Sustainability method.

Figure 3-4b provides the CDFs of total emissions for the Maximize Sustainability method, BAU, and Maximize VR method. The Maximize Sustainability method produces the smallest median total emissions, followed by BAU and Maximize VR. The emissions share similar shapes to Medium Office, with BAU and minimize emissions being normal. There is less separation between the CDFs when compared to Medium Office. Differences in the 25th, median, and 75th percentile of total emissions expressed as a percentage of the median BAU emissions are 16.81%, 20.98%, and 24.56% respectively. The overall improvement in total emissions compared to BAU is less than Medium Office despite the identical demand to supply ratio. Differences in the 25th, median, and 75th percentile of total emissions expressed as a percentage of BAU between Maximize VR and BAU are 44.15%, 63.83%, and 90.65%, higher than Medium Office (27.48%, 42.44% and 65.02%). This is due to the higher roof area/people parameter for the Apartment case. More catchment area to capture the available supply results in the yield of the system being better able to meet the demand.

(a)



(b)

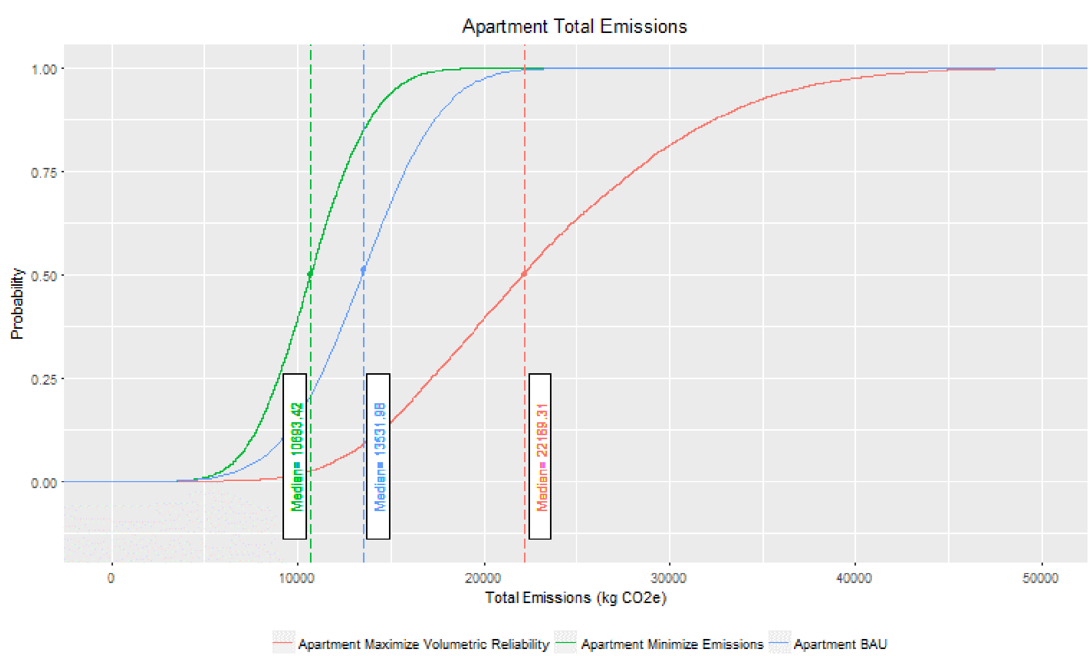


Figure 3-4: CDFs for Apartment Case: a) Volumetric reliability b) Total emission

3.5 House

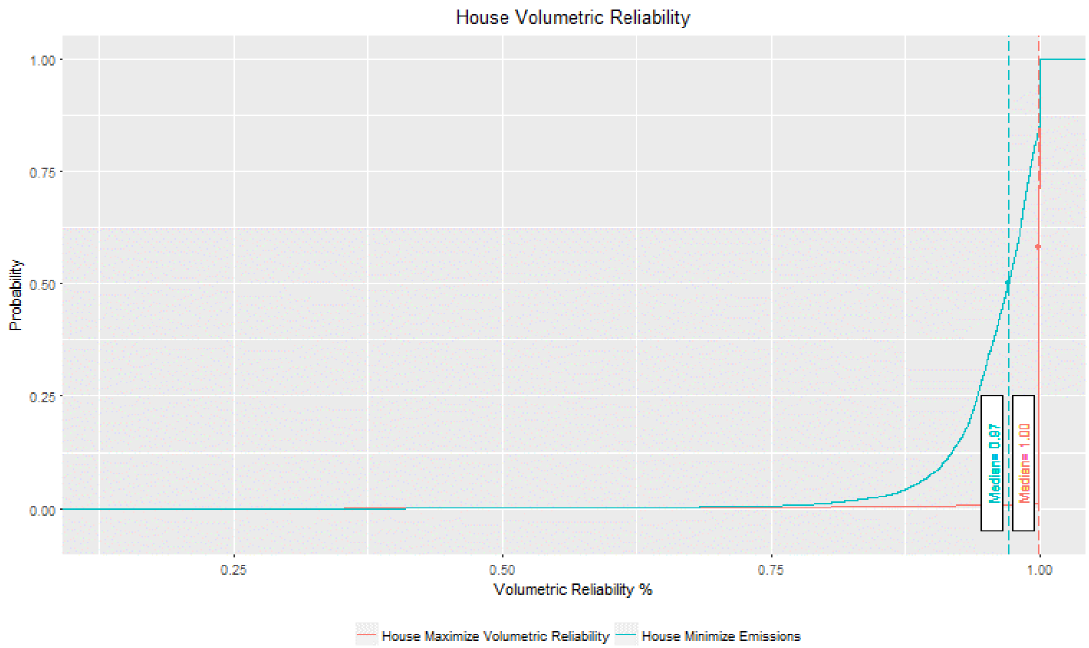
Figure 3-5a provides the CDFs of VR for the Maximize Sustainability and Maximize VR methods. For House, the median VR for the Maximize Sustainability and Maximize VR are 0.97 and 1.00 respectively. The distribution for Maximize VR is the same as that for Small Office in with nearly all the iterations of the simulations producing a VR of 1.00, the 1th percentile of VR is 0.99. This makes sense with both cases having demand to supply ratios of 0.4. However, the VR distribution for this case does not have the same shape as House, it appears to be truncated by the maximum VR of 1. This can be a result of the minimum tank size being enough to meet the maximum VR in most the simulations so there is not much difference if any between the VR that minimizes emissions and meeting the maximum VR.

Figure 3-5b provides the CDFs of total emissions for the Maximize Sustainability, BAU, and Maximize VR simulations. Comparing the median total emissions, the BAU produces the lowest emissions, followed by Maximize Sustainability and Maximize VR. The difference in emissions between the Maximize Sustainability and BAU expressed as a percentage of the median of BAU for the 25th, median, and 75th percentile are 119.99%, 149.52%, and 178.89% respectively. So, emissions are more than doubled with RWH, even under the tank sizes that produce minimum emissions for the RWH model.

The emissions results indicate that RWH should not be implemented in this case if the goal is GWP reduction. Tank emissions from even the minimum tank size negate potable water reductions resulting from RWH implementation. Simulations run with 50 gallons as the minimum, the size of a standard water heater, produce similar results (see Figure 3-

6). The distributions of total emissions are closer than with a 300 gallon minimum tank size, 30.84%, 26.35%, and 21.81% as a percentage of the median of BAU for the 25th, median and 75th percentile. A reason RWH might not be performing well in this scenario is that the demand is low enough that potable water emission reductions resulting from implementation are not high enough to negate tank emissions.

(a)



(b)

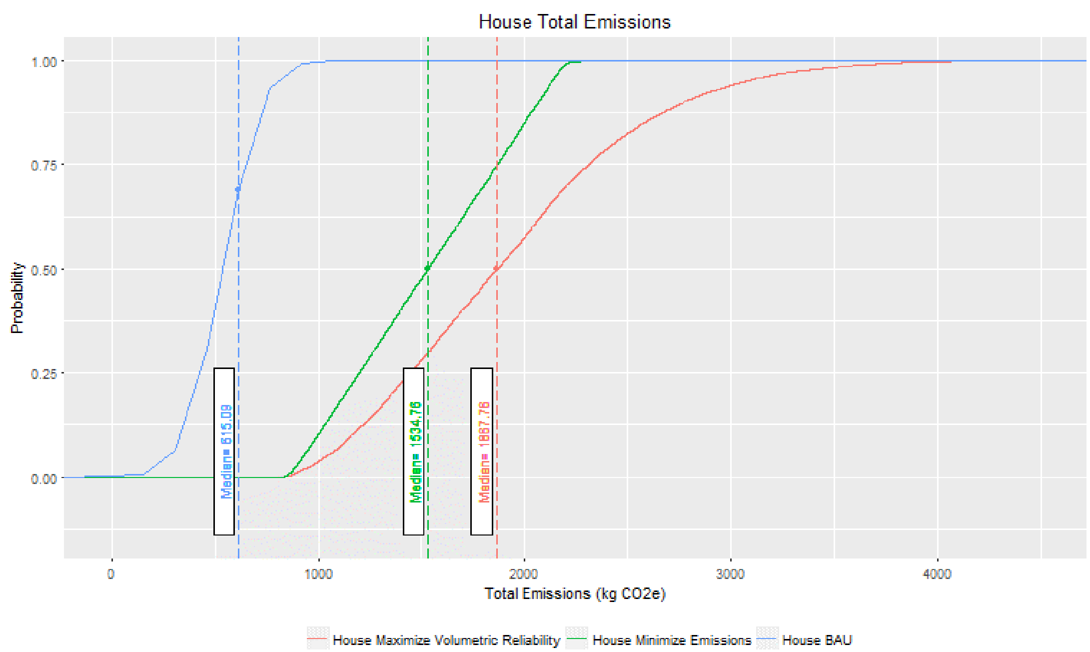


Figure 3-5: CDFs for House Case: a) Volumetric reliability b) Total emission

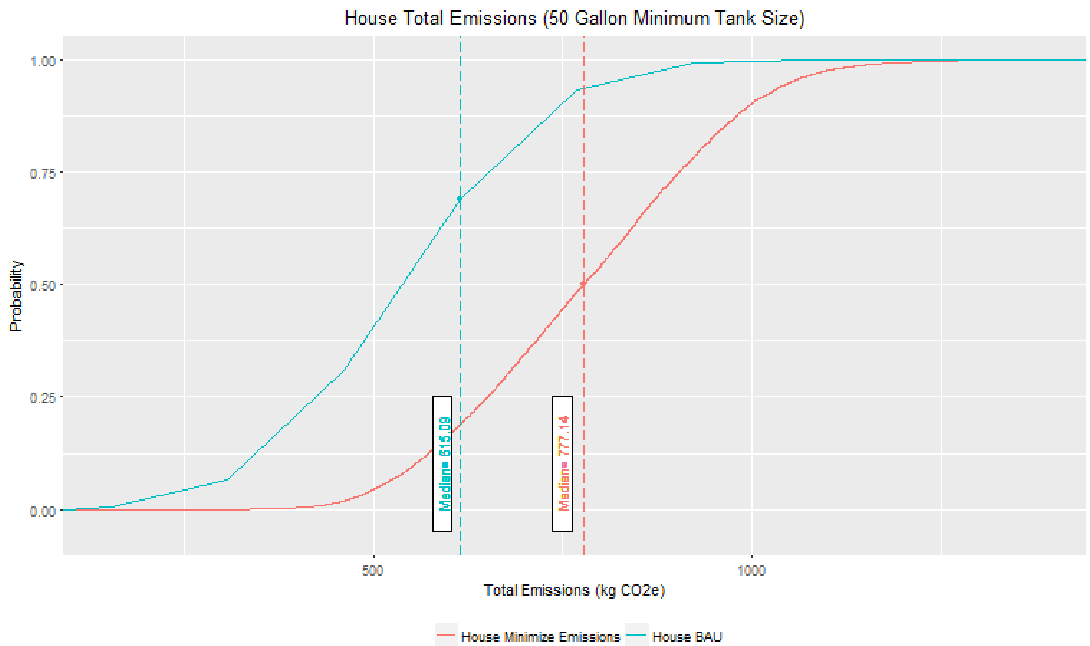


Figure 3-6: CDF of Total Emissions for Minimize Emissions Case and BAU with a 50 gallon minimum tank size

3.6 Comparison of the different building types

In all cases the Maximize Sustainability method produces lower median total emissions and VR than the Maximize VR method. Only in the House are the BAU total emissions lower than the Maximize Sustainability method. The Maximize Sustainability method generally produces RWH systems which result in lower GWP emissions than BAU.

The Maximize Sustainability method chooses the minimum tank size for many of the iterations throughout the five cases. While a nontrivial minimum occurs in the relationship between tank size and total emissions for a given building configuration, as indicated by the tank sizes selected for Large Office, this relationship only becomes important in systems with high overall demand. The best practice to maximize CO2 reductions with RWH might be to select tank sizes that are sufficient to collect the rainfall from the most frequent rainfall event for the climate.

3.7 Comparison of Methods with Identical Building Parameters: Total Emissions

Figure 3-7 illustrates a comparison of total emissions data between the two sizing methods for all the building cases where building parameters correspond one to one. Simulations were run with the same seed to achieve this. This was done to be able to compare the emission results for the two methods iteration by iteration with everything else being held constant. This provides information about how many iterations produced emissions that were identical or if the Maximize Sustainability method produced higher emissions due to error from @risk.

In all building cases, all iterations produced smaller or equal total emissions results for the Maximize Sustainability method. Only 3 iterations for Small Office and 1585 for House produced equivalent emissions between methods, the rest of the iterations for all building cases produced smaller emissions for the Maximize Sustainability method. This further strengthens the result of the random simulations, that for all five building cases, the Maximize Sustainability method generally produces lower total emissions than the Maximize VR method. A Wilcoxon signed rank test with a directional hypothesis that the current methodology produces greater total emissions than the proposed methodologies resulted in p values lower than 0.001 for all building cases, further supporting this.

A linear regression of the data was conducted with Excel's built in function and reported in Figure 3-7. Small and Large Office have good correlation (R^2=0.9352 and 0.9407 respectively), indicating a more linear relationship between methods for these two cases. House has a similar characteristic but to a lesser degree (R^2=0.6964). Medium Office and Apartment have moderate correlation (R^2=0.5391 and 0.4854 respectively). These last 3 cases show that while the relationship between methodologies can be more uniform in some cases, this does not hold true for all cases.

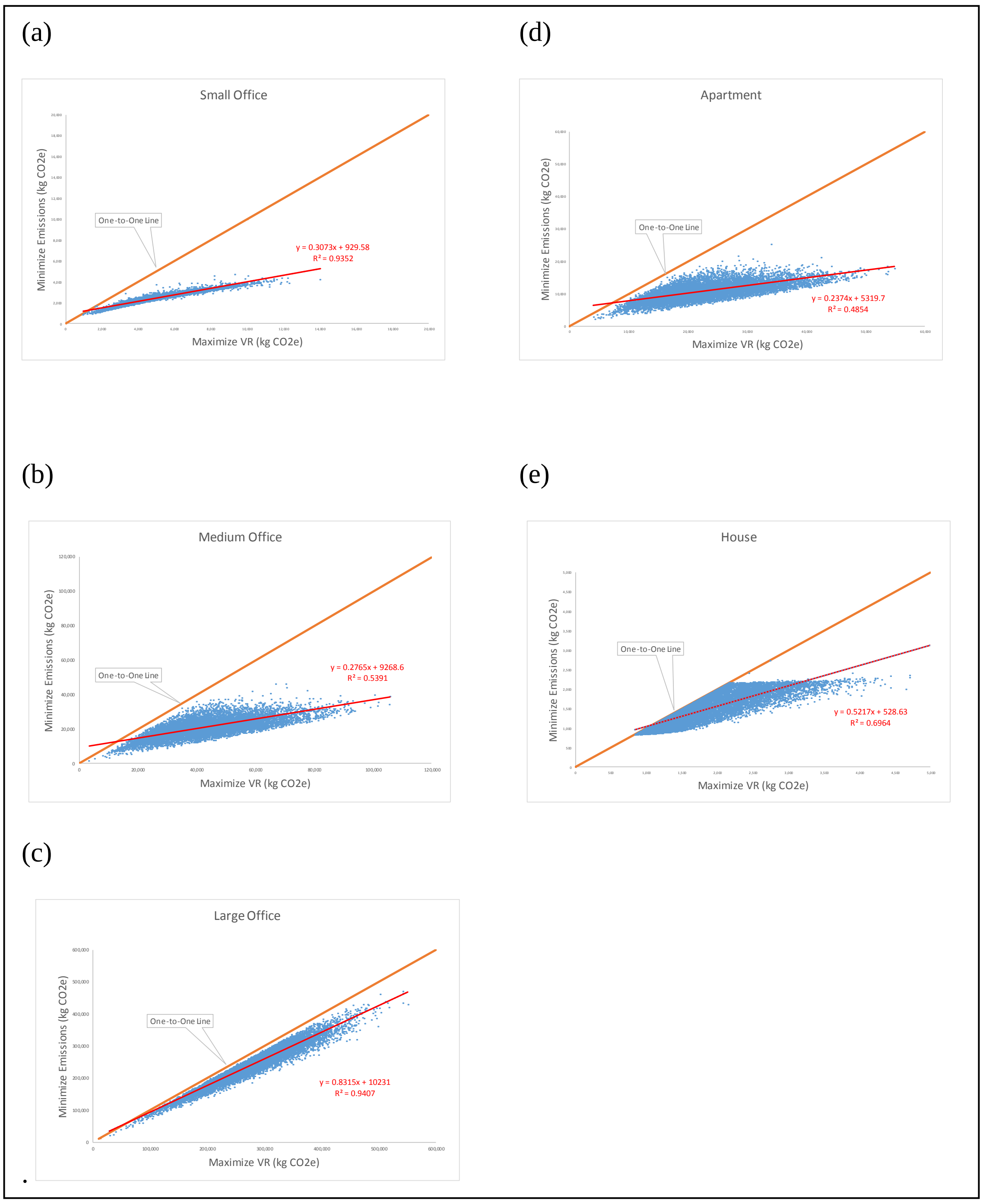


Figure 3-7: Comparison of Total Emissions for Current and Proposed Methodology: a) Small Office b) Medium Office c) Large Office d) Apartment e) House

3.8 Comparison of Methods with Identical Building Parameters: Volumetric Reliability

Figure 3-8 illustrates a comparison of VR between the methods for all the building cases where building parameters correspond one to one. Figure 3-8a and 3-8e, the Small Office and House show similarities, as would be expected from the CDF plots of VR in the random simulations. In each case the Maximize VR method produces VR of 1.00 for the majority cases while the Maximize Sustainability method produces VRs ranging from 0.19 to 1 for Small Office and 0.13 to 1 for the House.

The Medium Office, Large Office, and Apartment case display different trends. There is stratification of the data. It is possible that there could be a similarity in building characteristics between these separate linear trends. Further analysis of the data is needed to determine if this is the case.

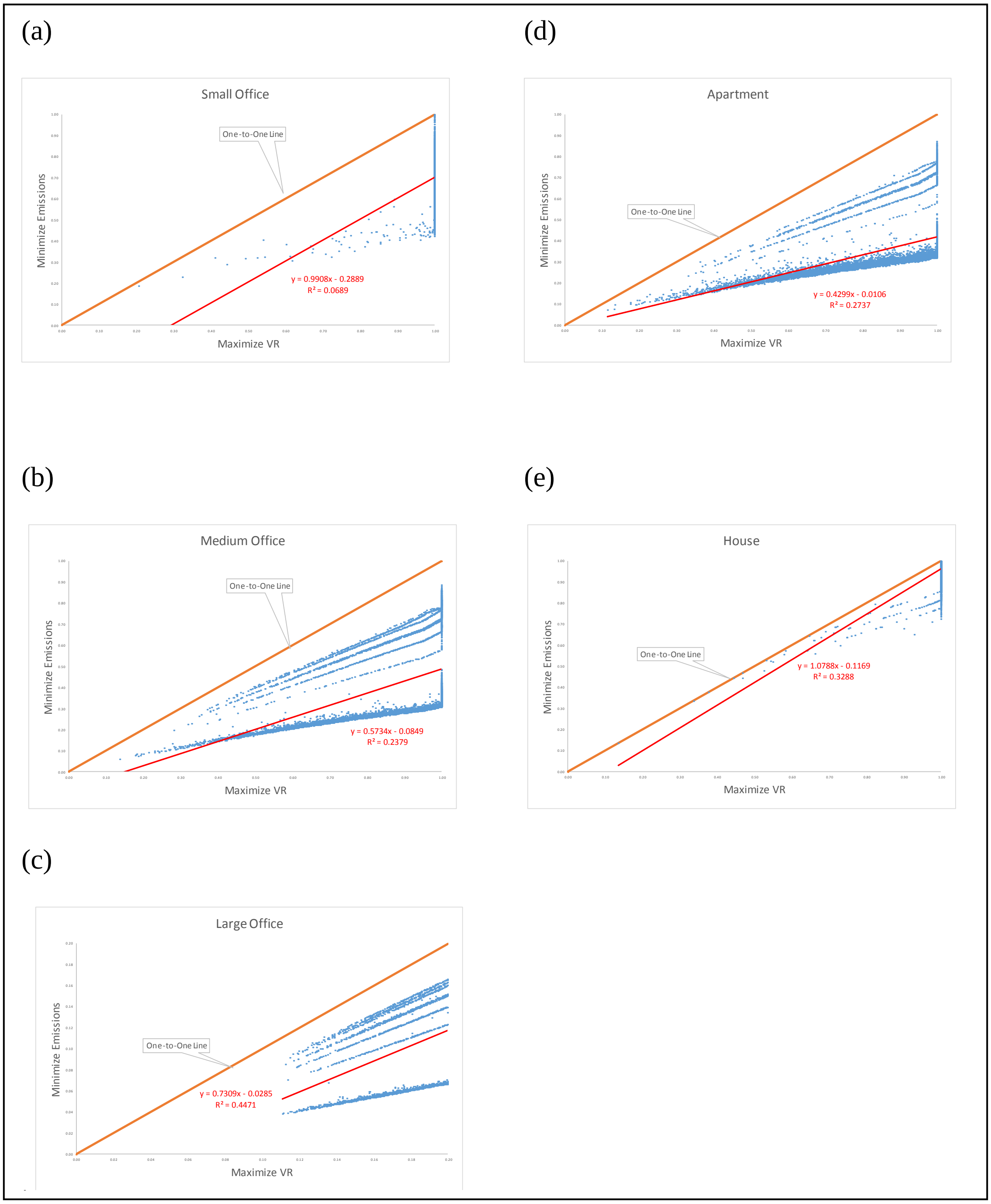


Figure 3-8: Comparison of Volumetric Reliability for Current and Proposed Methodology: a) Small Office b) Medium Office c) Large Office d) Apartment e) House

3.9 Limitations

As mentioned earlier the same rainfall pattern is run during the simulation 75 times. In practice weekly rainfall amounts will vary from year to year. Additionally, the rainfall is taken from 2014 Toledo airport data whose annual rainfall might not be reflective of the average year. To determine the effect that this might have on the results a sensitivity analysis was conducted detailed in section 3.10. Other limitations of the study include the exclusions of other components of a RWH system in the inventory including pumps, gutters, and piping. The additional GWP emissions from these components might reduce some of the emissions reductions over BAU in some of the scenarios. Finally, further data on the use of roof and tank materials in practice, would allow for more robust distributions to be applied to the runoff coefficient and tank material parameters.

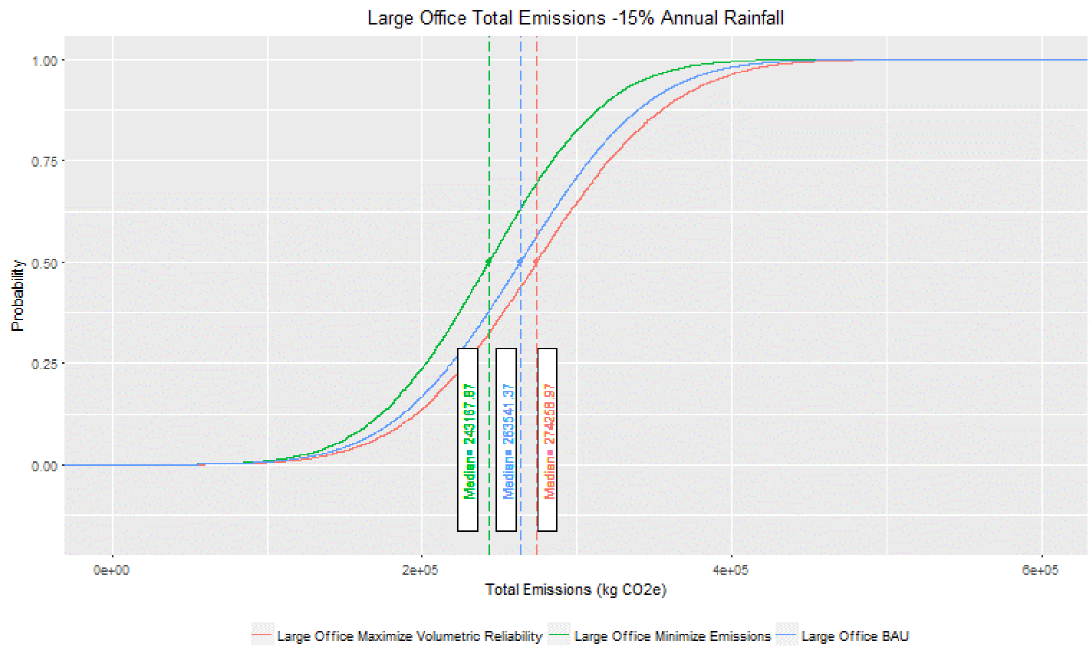
3.10 Sensitivity Analysis

Figure 3-9 provides the CDFs for Large Office with 15 percent less and more annual rainfall. This was done to determine the effect that rainfall has on emissions results. BAU results are shown on the graph for reference purposes but do not change as rainwater is not used in the BAU case. The simulation with 15 percent less rainfall resulted in an increase in median emissions of 0.03% and 1.75% for the Maximize VR and Maximize Sustainability respectively. The shapes of the CDFs are not different than the base simulation. The increase emissions for the maximize sustainability method is consistent with their being less rainfall available. The simulation with 15 percent more rainfall resulted in an increase in median emissions of 0.31% for the Maximize VR and a reduction of 1.80% for Maximize Sustainability. The increase in emissions for Maximize VR is likely due to the method producing larger tanks, due to the extra rainfall, where tank emissions increases are not sufficiently supplanted by potable water emissions reductions that result from greater rainwater capture. Again the shapes of the CDFs are not different than the base simulation. While causing small changes to the median emissions the fluctuation in rainfall does not result in a change in the qualitative interpretation of the Large Office results. Maximize Sustainability has lower total emissions than BAU and Maximize VR results in greater emissions than BAU. While a more thorough treatment of rainfall can improve the model it, other system parameters such as occupancy and roof area/people play a larger role in the total emissions results. This is demonstrated in Table 3.2 where the range in the change of the output mean as reported by @risk is provided for the various parameters.

Table 3.2: Change in Output Mean for Large Office

		Maximize Sustainability (Mean=239234.39)		Maximize VR (Mean=275512.34)	
	Correlation Orientation	Range of Change in Output Mean	% of Mean Change	Range of Change in Output Mean	% of Mean Change
People	Postive	206201.16	86.19%	233905.45	84.90%
Roof Area/People	Negative	17672.15	7.39%	60370.1	21.91%
Tank Emissions	Postive	15259.46	6.38%	6407.42	2.33%
Runoff Coeficient	Negative	10947.33	4.58%	6219.18	2.26%

(a)



(b)

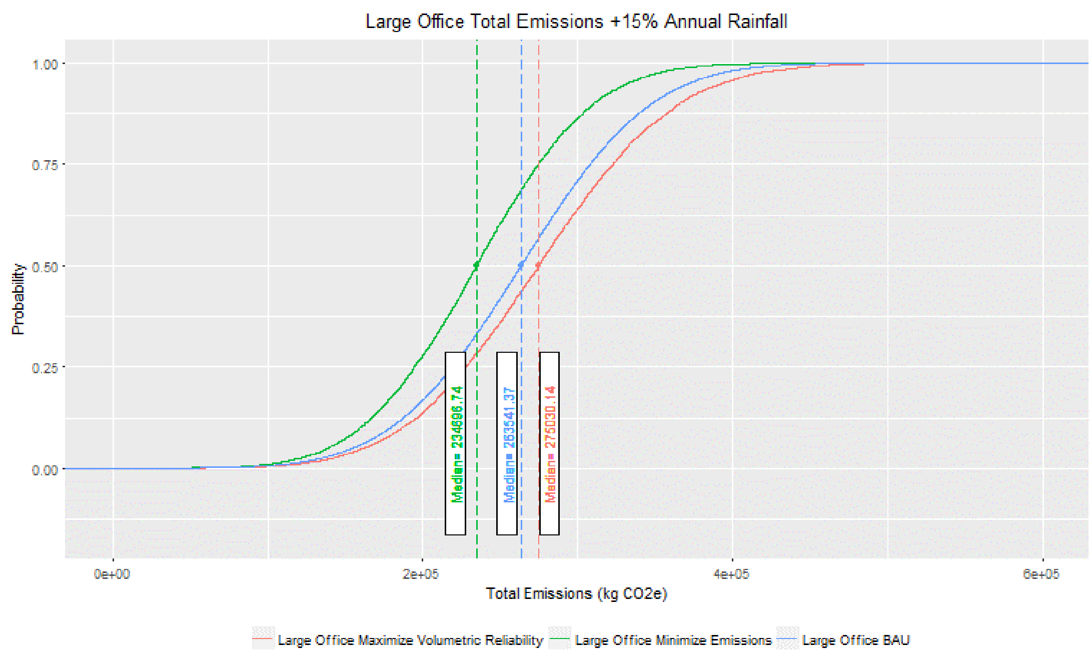


Figure 3-9: CDFs for Large Office Case: a) -15% Annual Rainfall b) +15% Annual Rainfall

Chapter 4

Conclusion

4.1 Conclusion

The purpose of this investigation was to determine under which conditions, if any, does a lower Global Warming Potential (GWP) result when sizing a RWH storage tank to minimize GWP (Maximize Sustainability method) rather than sizing in the traditional way of maximizing system reliability (Maximize VR method). My hypothesis was that there are certain building types that will be sensitive to the sizing methodology and will result in lower emissions with the Maximize Sustainability method. To answer this question simulations of models of RWH systems for five basic building cases were conducted under a range of variable building parameters within each building case. The results indicate that there is a difference in resulting CO2 emissions resulting from the sizing methods, and that the Maximize Sustainability method leads to reduced CO2 emissions in all the building cases except for house.

Furthermore, the results demonstrate the nonlinear relationship of system emissions as a function of tank size, with the use of real world building cases. This occurs because of the inverse relationship between tank material and potable water consumption also as a function of tank size, and their resulting component emissions. The Maximize Sustainability method functions based on this fact, sizing the tank to balance the relationship between increasing tank material and reduced potable water consumption with increasing tank size. One can size the tank to produce lower overall emissions than BAU, in most cases, if the tank is sized by considering the relationship between tank material emissions and potable water emissions. Further work can be done to determine if the additional components of a RWH system such as filters and piping will negate the reductions in CO2 emissions relative to BAU. Further work can also be done to determine if similar relationships exist with other environmental metrics such as eutrophication and ozone depletion.

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Appendix A

Simulation Settings: Iterations

a) b)

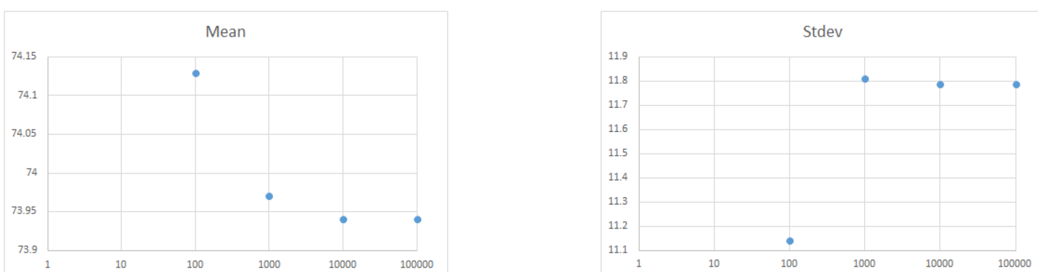


Figure A-1: Statistical results for simulations with different number of iterations a) Mean b) Standard Deviation

The number of iterations was chosen by conducting preliminary simulations and comparing the change in the sample mean and standard deviation. When the change in the sample mean and standard deviation was less than 0.01% the number of iterations were considered adequate. Figure A-1 show the results of the analysis.

Appendix B

Minimize Emissions Tank Size Solver

The Excel solver is used to solve for the tank size that minimizes emissions for each iteration of the simulations through a VBA subroutine (provided below). The subroutine sets the initial value to 300 gallons, the minimum tank size selected for the RWH systems, to provide the solver an initial value close to the anticipated tank size. The solver is set to MultiStart with a population size of 20. The population size was chosen through trial and error to give a sufficient pool of initial values for the solver to converge onto the minimum tank size, and was tested for a variety of test cases covering the various simulation cases. Tank size is constrained from a minimum of 300 to a maximum of a 1,000,000. In addition, tank size is constrained to integer values and the precision for the constraints is set to 0.001. Convergence was set at the excel default value of 0.0001. The precision for the constraints and convergence for the solver were chosen high enough to meet sufficient accuracy for the problem, but low enough that solutions converge quickly enough so that simulations aren't too lengthy.

```
Sub SolveMinMulti()
    SolverReset
    Worksheets("Min").Range("M2") = 300 'Tank size cell initialized to 300
    SolverOptions precision:=0.001, MultiStart:=True
    SolverOK setCell:=Worksheets("Min").Range("R19"), _
    MaxMinVal:=2, _
    ByChange:=Worksheets("Min").Range("M2"), _
    EngineDesc:="GRG Nonlinear"
    SolverAdd CellRef:=Worksheets("Min").Range("M2"), _
      Relation:=3, _
      formulaText:=300 'Minimum tanksize
    SolverAdd CellRef:=Worksheets("Min").Range("M2"), _
      Relation:=1, _
      formulaText:=1000000 'Maximum tanksize
    SolverAdd CellRef:=Worksheets("Min").Range("M2"), _
      Relation:=4
    SolverOptions PopulationSize:=20
    SolverSolve userFinish:=True
    GoTo End_Sub
End_Sub:
  Exit Sub
End Sub
```

Appendix C

Maximize Volumetric Reliability Tank Size Solver

The Maximize Volumetric Reliability Tank Size Solver subroutine (provided below) was based of binary search. Minimum and maximum tank size were set the same as for the Excel solver. Binary search works due to the logarithmic relationship between VR and tank size. As tank size increases VR increases until the maximum VR is reached, with the rate at which VR increases decreasing as the tank size converges to the smallest tank size which results in maximum VR. The subroutine works using this fact to search for the smallest tank size for which an increase in tank size will not result in an increase in VR above a certain threshold (0.001). The subroutine first checks if the VR difference resulting from the minimum and maximum tank size is below the threshold. If it is, the tank size selected is the minimum tank size. If it isn't, the algorithm compares the resulting VR from the tank size between the minimum and maximum tank size to the one resulting from the maximum tank size to determine if the VR from the maximum tank size is higher. If it isn't, the middle tank size is set to the high tank size and a new middle is computed between the minimum tank size and the new high tank size. If it is, then the middle tank size is set to the low tank size and a new middle tank size is computed between the new low and the maximum tank size. This continues until the difference between the maximum and minimum tank size is below the threshold, at which point the minimum tank size at this point is selected as the tank size.

```
Public Sub MaximizeVRBinary()
  Worksheets("Min").Range("M2") = 300
  TankLow = 300 'Initialized for low range for tanksize
  TankHigh = 1000000 'Initialized to high range for tanksize
  delta_VR = 999999999 'initialize delta vr to arbitrary high value
  precision = 0.001 '0.001 default
  While (Abs(delta_VR) > precision)
    Worksheets("Min").Range("M2") = TankHigh
    Calculate
    VRHigh = Worksheets("Min").Range("L61")
    Worksheets("Min").Range("M2") = TankLow
    Calculate
    VRLow = Worksheets("Min").Range("L61")
    delta_VR = VRHigh - VRLow
    If Abs(delta_VR) > precision Then
    TankMid = Round((TankHigh + TankLow) / 2)
    Worksheets("Min").Range("M2") = TankMid
    Calculate
    MidVR = Worksheets("Min").Range("L61")
    If MidVR < VRHigh Then
      TankLow = TankMid
    Else
    TankHigh = TankMid
    End If
  Else
  Worksheets("Min").Range("M2") = TankLow
  TankHigh = TankLow
  End If
  Wend
End Sub
```

Appendix D

Wilcoxon Signed Rank Test

As described in section 3.7 a Wilcoxon Signed Rank Test was run on the paired data sets of total emissions produced by running simulations with @Risk with the same seed for the two methodologies for all the building cases. This was to test the null hypothesis that the two sets of samples have identical medians with the alternative directional hypothesis that the median of the current methodology is higher than the proposed methodology. A t-test would not be applicable for this data due to the distributions of the data not following the normal distribution. Results of the Wilcoxon Signed Rank test are reported in table D-1. The test was performed in R.

Table D.1: Results of Wilcoxon Signed Rank Test. V is the sum of the positive ranks.

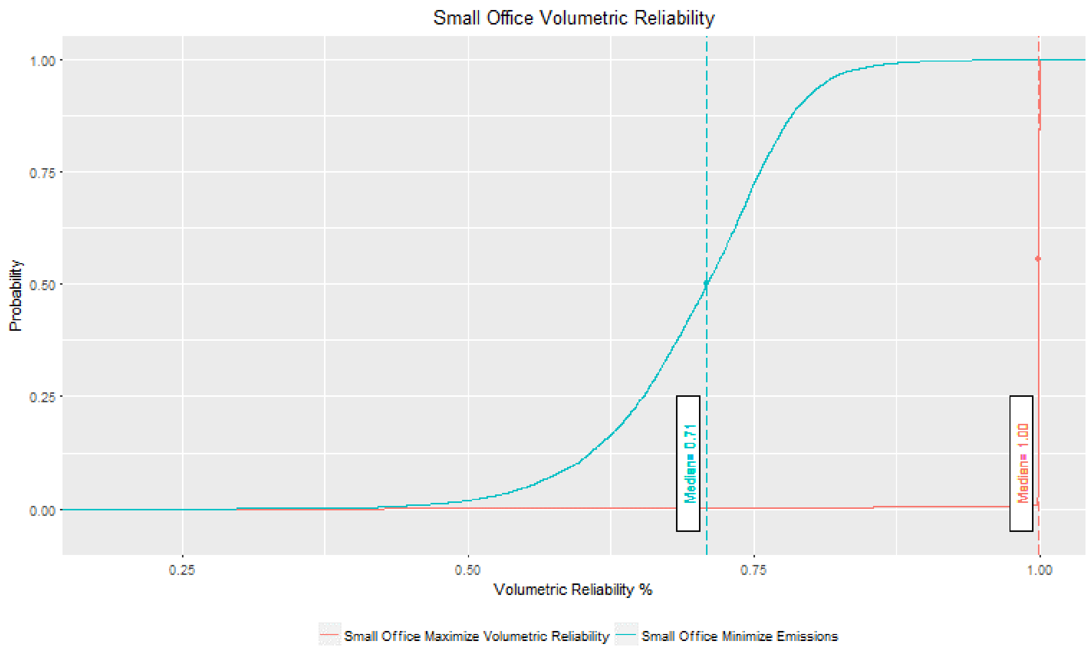
Case	**V**	**P value**
Small Office	49975003	<0.001
Medium Office	50005000	<0.001
Large Office	50005000	<0.001
Apartment	50005000	<0.001
House	35410320	<0.001

Appendix E

Additional Detail on Same Building Parameter Simulations

Figures S-2 through S-6 provide the CDFs of these simulations as provided for the random simulations for sections 3.1 through 3.5. The BAU curves are of the same simulations described in 3.1 to 3.5. CDF shapes between the random simulations and the simulations run with the same seed are very similar, as would be expected if the number of iterations for the simulations were sufficient for the simulations was sufficient. Medians for the current methodology vary by a maximum of 0.30% between the two sets of simulations.

(a)



(b)

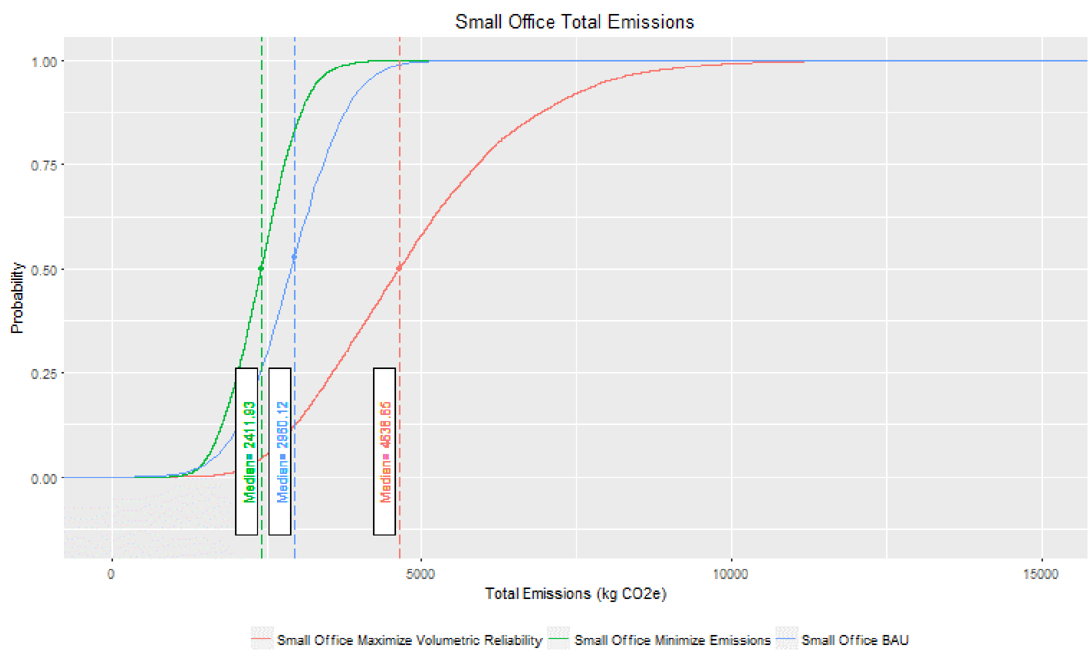
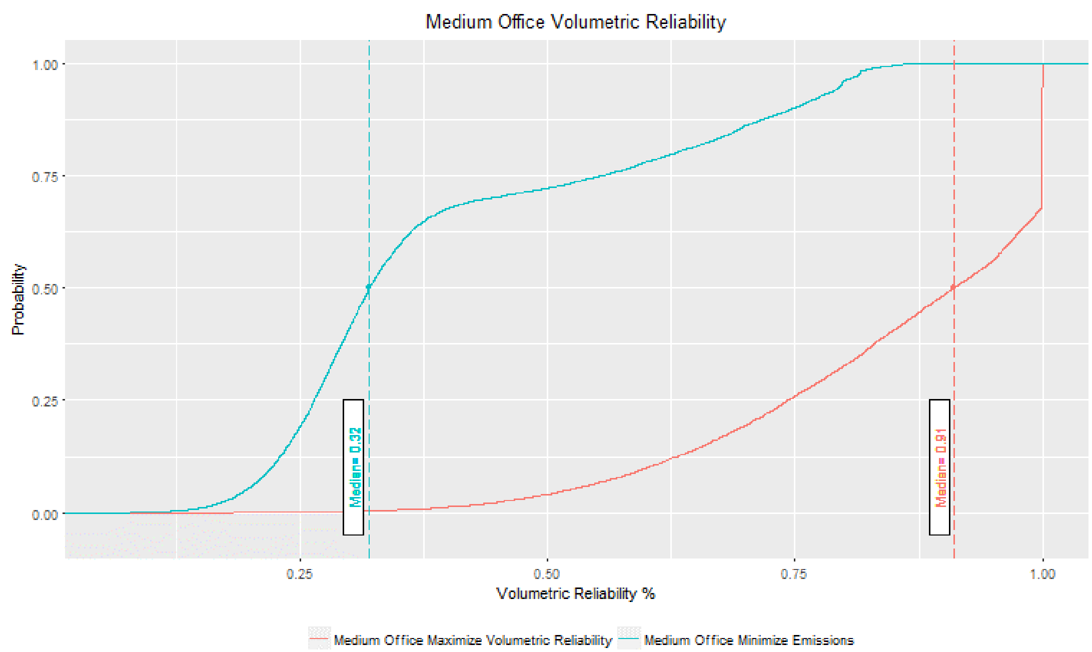


Figure E-1: CDFs for Small Office Case: a) Volumetric reliability b) Total emission

(a)



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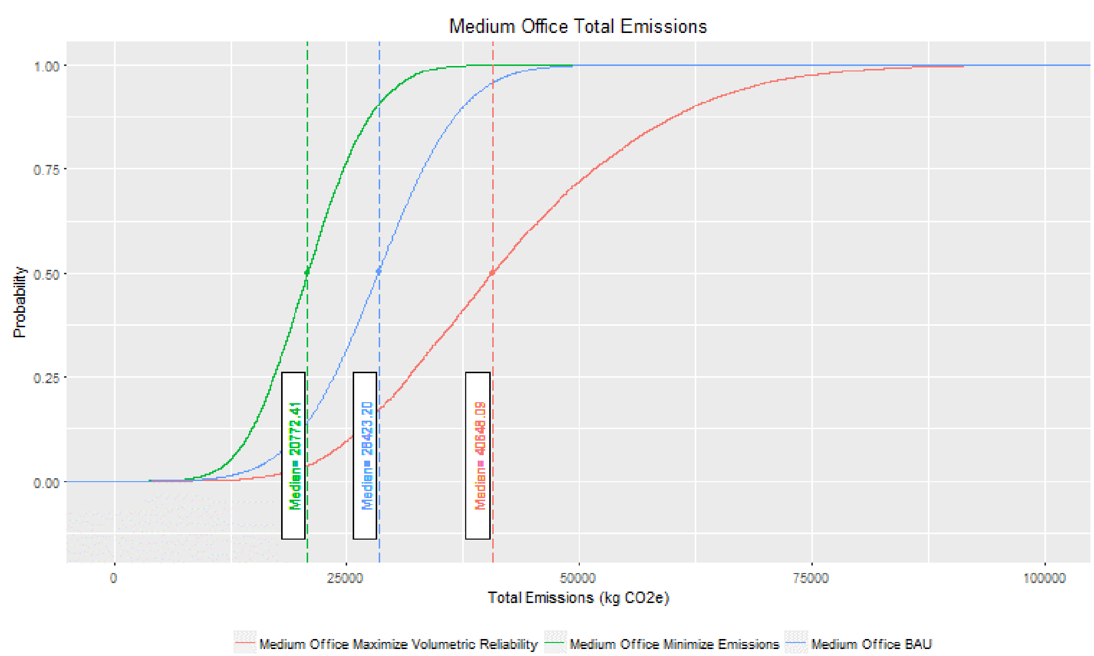
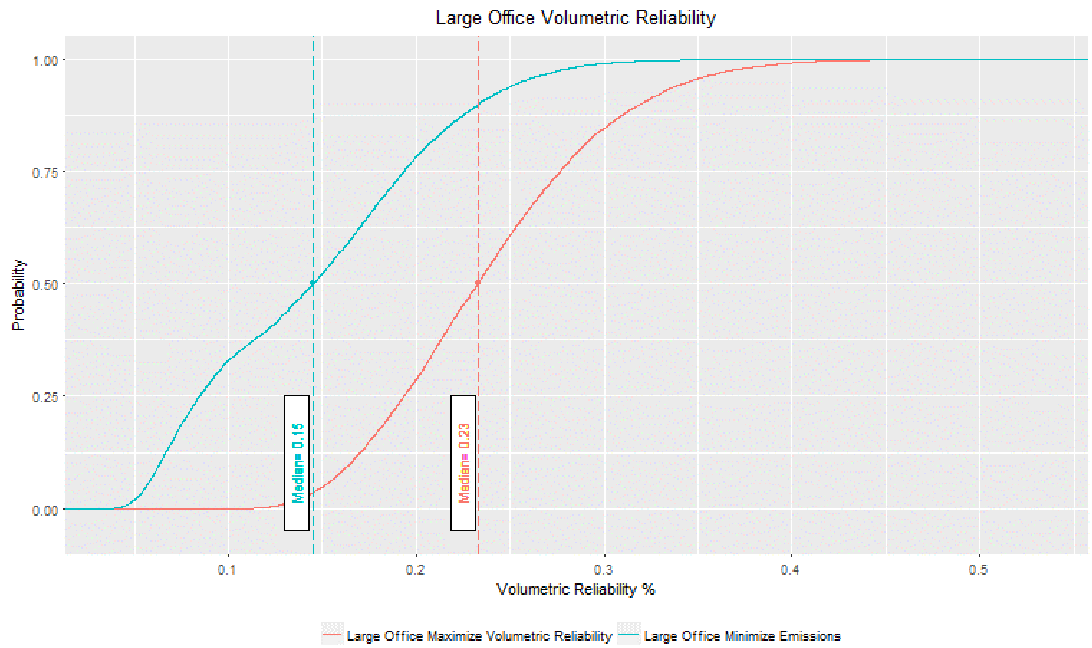


Figure E-2: CDFs for Medium Office Case: a) Volumetric reliability b) Total emission

(a)



(b)

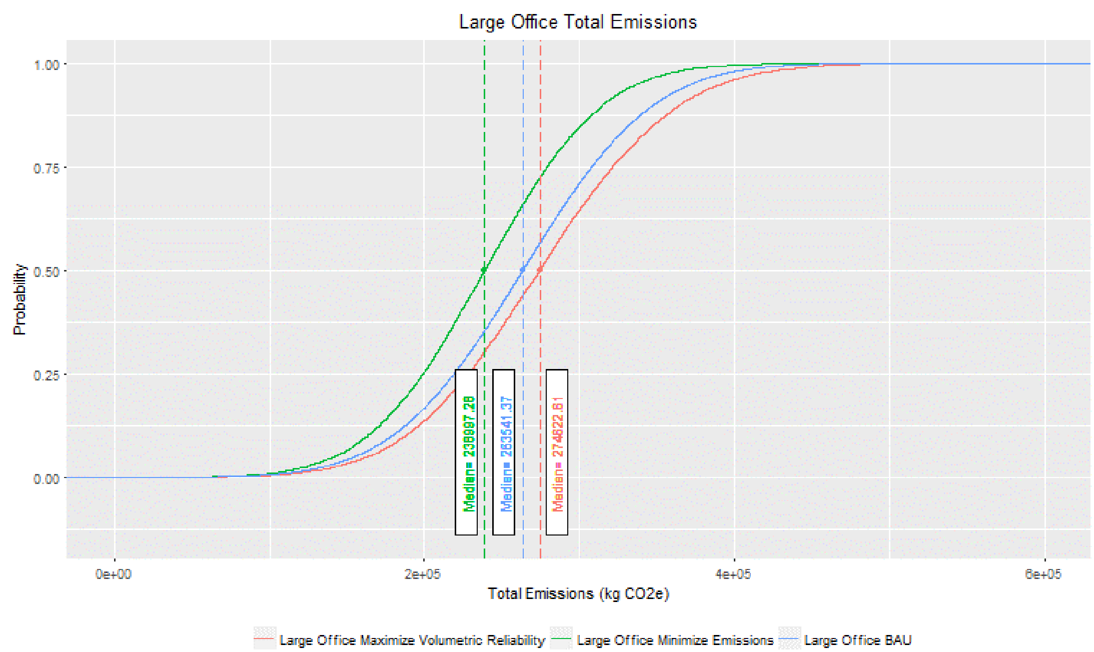
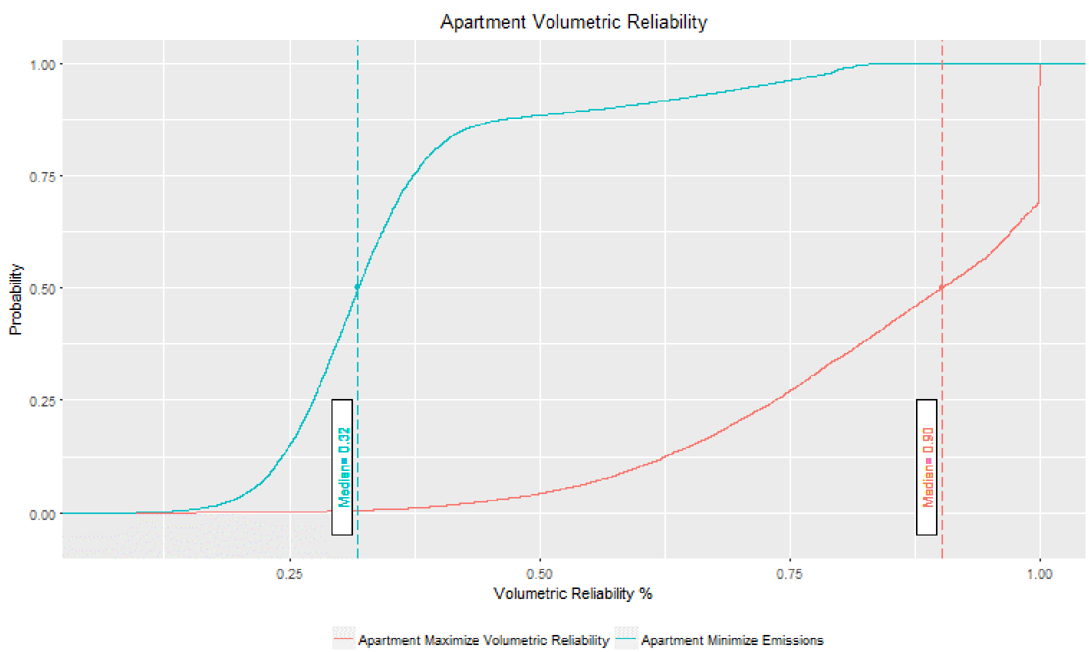


Figure E-3: CDFs for Large Office Case: a) Volumetric reliability b) Total emission

(a)



(b)

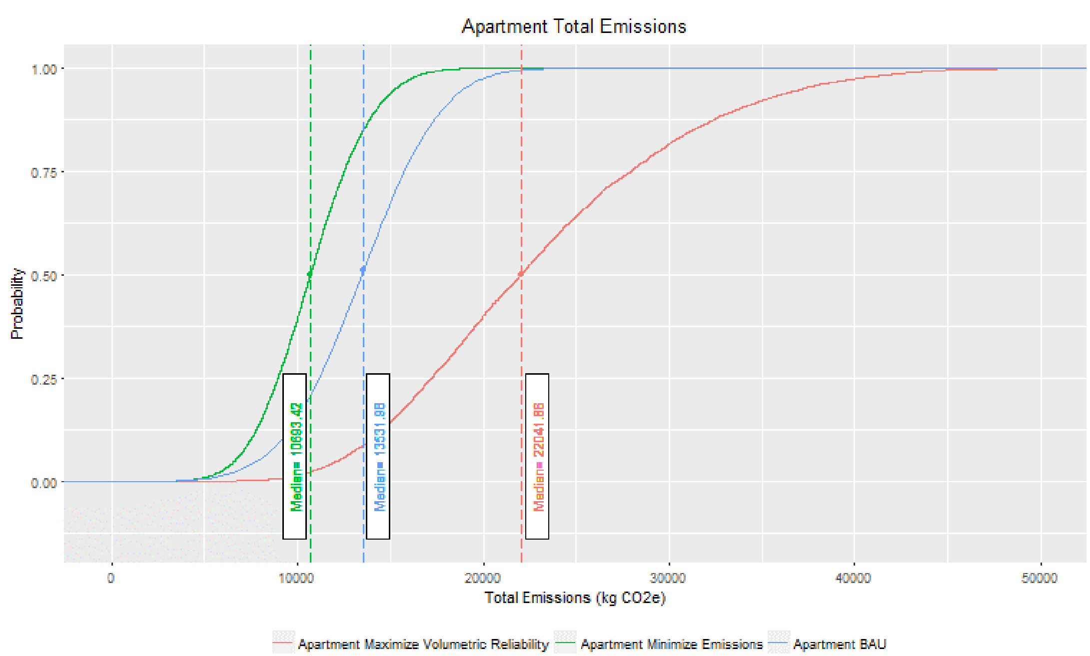
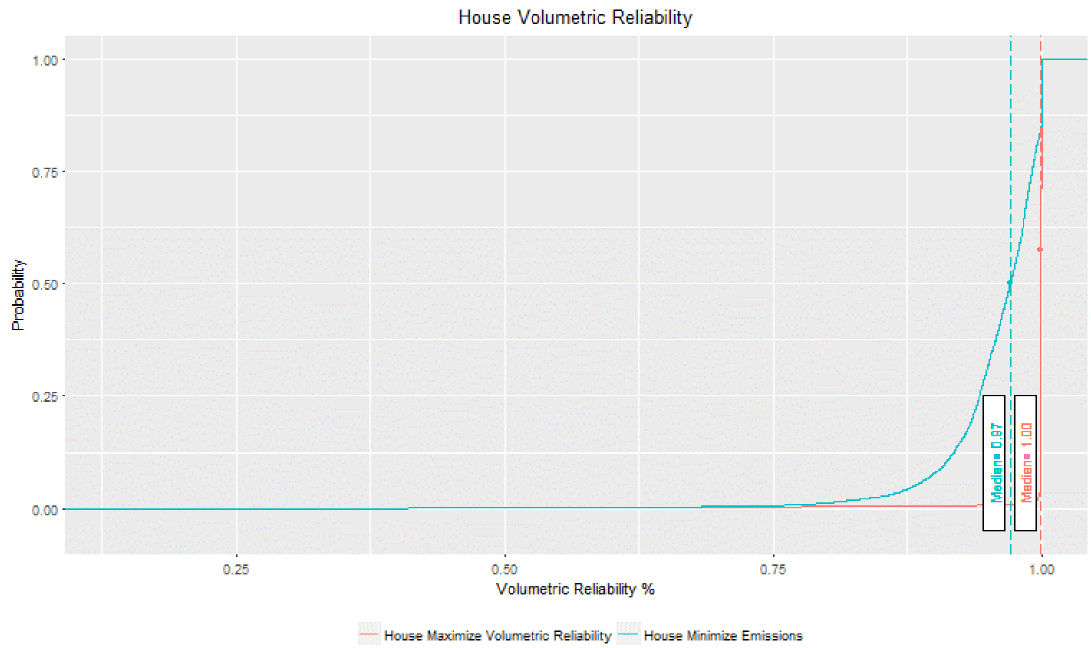


Figure E-4: CDFs for Apartment Case: a) Volumetric reliability b) Total emission

(a)



(b)

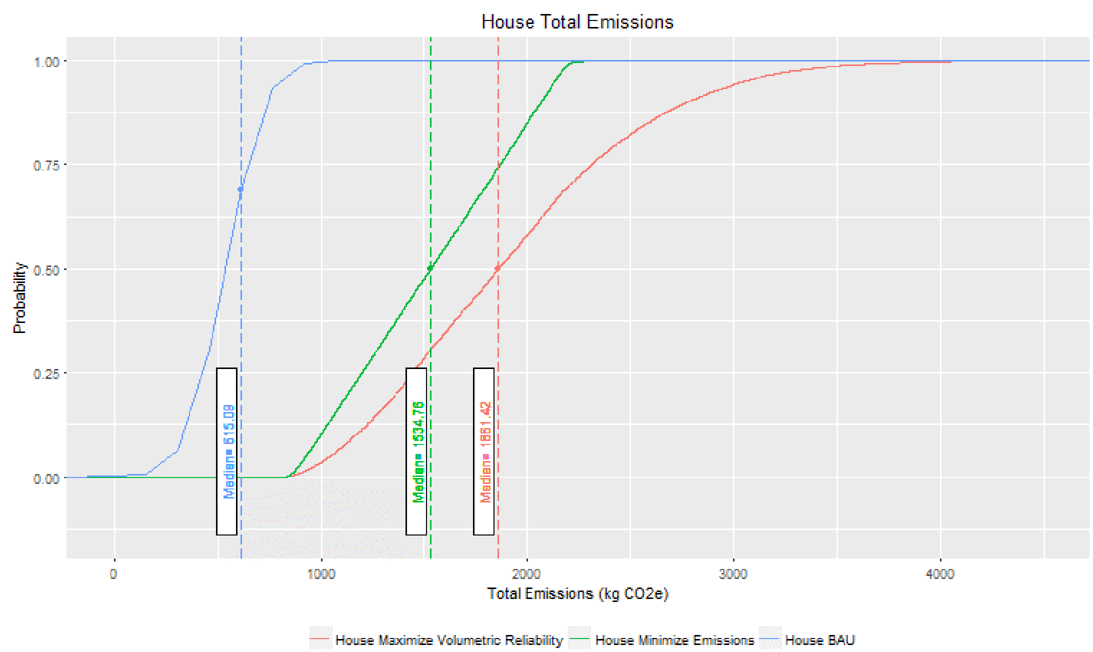


Figure E-5: CDFs for House Case: a) Volumetric reliability b) Total emission