Lappeenranta University of Technology
School of Engineering Science
*Erasmus Mundus Master's Programme in Pervasive Computing & Communications for sustainable Development* PERCCOM

**Phoebe Mutua**

# DATA CENTER PERFORMANCE COMPARISON FRAMEWORK BASED ON BIOMIMICRY

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**Supervisors**: Professor Eric Rondeau (Université de Lorraine)
Dr. Jean-Phillipe Georges (Université de Lorraine)
Dr. Sylvain Kubler (Université de Lorraine)

**Examiners** : Professor Eric Rondeau (Université de Lorraine)
Professor Jari Porras (Lappeenranta University of Technology)
Associate Professor Karl Anderson ((Luleå University of Technology)

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## ABSTRACT

Lappeenranta University of Technology
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Phoebe Mutua

**Data Center Performance Comparison Framework based on Biomimicry**

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Examiners: Professor Eric Rondeau (Université de Lorraine*)*
Professor Jari Porras (Lappeenranta University of Technology)
Associate Professor Karl Anderson ((Luleå University of Technology)

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The increase and demand for fast, efficient data processing and storage services coupled with the high energy usage necessitate the need for changes in the design and operations of the data center for improved performance. To efficiently appraise data centers, all the components that make up the data center must be examined. There are numerous data center metrics available today which can be categorized into energy efficiency metrics, green metrics, cooling metrics, performance metrics, storage metrics, network metrics, security metrics and financial metrics. Therefore, this study focuses on analyzing data centers sustainability with respect to nature laws and showcasing in a simple understandable manner, the holistic global view of their performance which is beneficial for continuous improvements and informed decision making for future scaling of services.

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## TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| AHP | Analytic Hierarchy Process |
| DEA | Data Envelopment Analysis |
| MAGDM | Multi-Attribute Group Decision Making |
| MO-GA | Multi-Objective Genetic Algorithm |
| SLA | Service Level Agreement |
| SWARA | Stepwise Weight Assessment Ratio Analysis |
| TCO | Total Cost of Ownership |
| VIKOR | VIseKriterijumska Optimizacija I Kompromisno Resenje |

# 1 INTRODUCTION

The rapid growth of data centers in the world is driven by the users need for a fast and efficient data processing and storage services. The abstraction of the Total Cost of Ownership (TCO) makes data centers more ideal for users [2]. The operations of a data center should always provide high reliability and availability to reduce the financial impact caused by downtimes. As data centers strive to stay competitive and attract more business, they must ensure that their processes are efficient and that they are able to manage their operational costs to realize gains from their venture.

The demand globally signify that data centers should operate 24 hours in 365 days which requires more resources to keep it on. Currently, the greatest challenge in most data centers is the exponential rise in energy consumption. ICT uses 1,500 TWh of electricity which is approximately 10 percent globally. In addition to the high energy usage, ICT contributes to 2 percent of the global carbon emissions with data centers accountable for 14 percent of the total ICT footprint [3].

Data center metrics can be used to evaluate the performance of data centers to ensure continuous improvements and accurate decision making for future growth. The key areas of measurements can be classified as energy efficiency, greenness, performance, storage, network, thermal and air management, cooling, security and financial impact. These areas have metrics that are interrelated which can create complexities during assessments. With over 130 metrics [3], it is almost impossible to provide a simple understandable global overview of the data center especially to executives who most of the times are not IT experts and can be even harder for IT experts to objectively analyze the data center's performance since there is not automated system to calculate all these metrics. The complexity presented from analyzing metrics of such magnitude can be difficult to decipher. In pursuance of making changes in the data center through enhanced energy efficiency, reduced emissions and reduced e-waste, there needs to be a comprehensive appraisal of all the components inside it and therefore it's important to have a detailed evaluation of all metrics for a global representation.

The continued harm on the environment is because man has evidently attained a cap on nature's resilience. Nature has been able to thrive for over 3.8 billion of years therefore, it has significant information on what works and what is good for the earth. Janine Benyus in her book "Biomimicry: Innovation inspired by Nature" proposes ten rules of a mature ecosystem which provides us with guidance on how businesses can operate sustainably [4]. These complex approved strategies support businesses to thrive as mature ecosystems. In this study, the data center metrics will be translated using these principles of a mature ecosystem to produce an easy, understandable global representation of the data center's performance for optimum operation.

Nature's competence and its harmonious coexistence for over 3.8 billion years, provides us with models which can transform our consumption of resources, waste management and environmental conservation in a rational and sustainable manner.

## 1.1 Motivation

This study seeks to make comparison of data centers performance easy to understand especially for Non ICT experts and also ICT engineers using Nature metrics (10 Biomimicry Laws) to provide them with a simpler way of evaluating performance and making important decisions such as data center design, location, operations improvements, and future growth. The holistic analysis and overview of data centers impact on the environment provides users with a basis to make better decisions when choosing data centers. This also ensures that data centers continually remain in balance with the biosphere by ensuring their activities do not harm the environment.

To objectively measure and assess the data center conduct with the magnitude of data center metrics available and metrics contradiction can be a very complex process. For instance, Water usage is key when designing, choosing the location and activities of data centers, however, there is a trade-off when it comes to the use of water, that is, increase water use and decrease energy use or increase water energy use and decrease water use. It is important to note that studies show that a data center can drain an Olympic-sized pool in just two days [5]. Water is just one example, therefore, a proper conclusion in decision making process can be very difficult. As a result, this research will make use of Analytic

Hierarchy Process (AHP) to administer a realistic decision that considers the importance of each element in the criteria and sub criteria and other alternatives that contribute to the goal of a sustainable data center [6].

## 1.2 Problem Definition

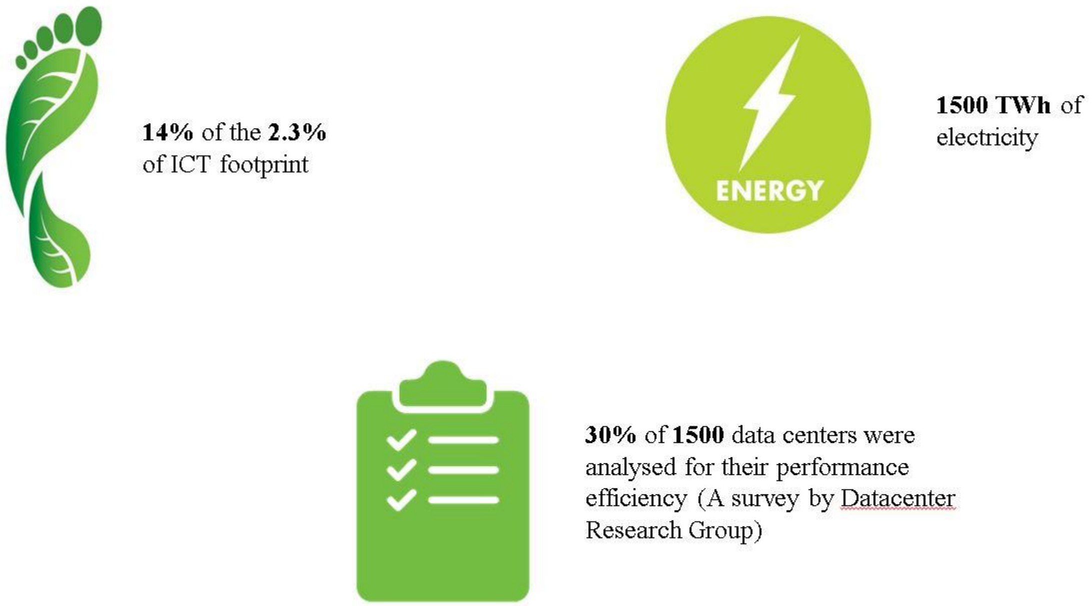


**Figure 1. Problem Definition**

The growth and increased demand for ICT and cloud services for data processing and storage has resulted into a high growth of large scale data centers globally to meet these needs. The challenge that is presented by the increased growth of data centers is high energy consumption which imply increase use of resources, emissions which are harmful to the environment and high operational costs. For instance as shown in figure 1 above, Data centers emissions are 14% of the 2.3% of ICT Carbon footprint [3]. Globally ICT infrastructures use nearly 1500 TWh of electricity which is approximately 10% worldwide consumption which lead to high operational costs [3]. These issues can have a significant impact on decisions such as design, location and growth of data centers. To mitigate these effects operations need to be optimized and energy-efficient techniques adopted to reduce the impact on limited earth resources and the environment.

In 2008, a survey [7] conducted by Datacenter Research Group on 1500 data center owners and operators showed that only 30% analyzed their data center performance efficiency. The rest, 70% did not see the importance of analyzing their efficiency which can be attributed to the complexity and contradictions in metric interpretations especially for decision makers who in some cases are not IT experts and have to rely on their ICT engineers analysis.

## 1.3 Delimitations

The constraints that manifested during the study include: lack of availability of data from data centers, therefore the data used is from scenario assumptions using the Cooling Economizer Mode PUE calculator provided by Schneider, data on energy consumption and Carbon emissions of the different energy technologies is from the International Energy Agency and information on the data center metrics came from The Green Grid.

There are over 130 data center metrics with some metrics being difficult to evaluate due to ambiguities. Therefore, there is a high probability of subjective inferences during the scrutiny of such metrics. The data center metrics provide a lot of contradictions and therefore can be difficult to make conclusive deductions. For instance, water is a resource that is a key determinant of the location and operation of the data center [8]. It's usage however has to be minimized but on the contrary, when you minimize water usage you increase electrical usage and costs associated with it. Therefore, it is very difficult to objectively decide on this tradeoff.

## 1.4 Research Objectives and Questions

This research aims at making data centers performance comparison to provide users and decision makers with an easy assessment of data centers for provision of services and continuous improvement. The sustainable analysis of data centers ensures that the positive and negative impacts on the planet are monitored and controlled.

The research questions that the study seeks to answer are:

- How can we reduce the complexity of data center metrics while assessing the positive and negative impacts of data centers on the planet?
- How can Biomimicry influence the design and operation of data centers?
- How can we holistically compare data centers performance in a simple understandable manner?

To answer these questions, the study adopted the research methodology through a five-phased approach that focused on identifying the gaps that the study seeks to address, reviewing of existing data center metrics and performance assessment tools, setting up of the data center scenario for examination of the positive and negative impacts, testing of the scenario with different criteria and finally data analysis and validation for decision-making and improved performance. This is detailed further in the research methodology as outlined in section 3 of this report.

## 1.5 Structure of the thesis

This thesis paper is organized as follows:

- The first section on the research background, motivation and delimitation of the study.
- The second section which highlights the related work and existing frameworks that compare data centers performance and existing gaps.
- In the third section, we will discuss the methodology and implementation of the study solution.
- In section four, we will delve on the case study analyze the results and discussions from the scenario.
- Finally in the fifth section we conclude and discuss future work on the research topic.

# 2 RELATED WORK

The analysis of data centers performance indicators is important because it is difficult to manage efficiency when you do not have tangible measurements. Through appraisals, data center executives can be able to determine their resource consumption, the level of greenness of the data center, and plan for expansion to accommodate new demands while evaluating their return on investment. This information allows data centers to stay competitive and continually improve their processes.

A survey [7] conducted by the Datacenter Research Group in 2008 on 1500 data center owners and operators showed that only 30 percent of the respondents analyzed their data center efficiency while the rest of the respondents did not see its importance. This can also be attributed to the complexity provided by the metrics and the difficulty of their interpretations especially for not IT executives who make valuable decisions regarding the data center.

Data centers increased evolution and competition has led to the need to improve performance and increase energy efficiency in operations. In 2010, data centers were consuming about 1.5% of the world's energy and with advancements in technology performance, internet, data and storage demands keep increasing then the increase in energy consumption [9].

Increasing demands for faster data processing speeds and efficient network capabilities necessitate the need for data centers to have high performance computing. The top 500 supercomputers performance has over the years increased at high rate ro meet the high performance demands as highlighted in figure 2 [9]. This growth implies the need for increased energy, network performance and increased resource usage in the development of high performance computing devices. Therefore, standards must be established that support the design and develop of systems and solutions that are sustainable as well as enable informed decision-making in organizations for cost saving and improved performance. This is because data centers rapid growth and establishments will continue to deplete the finite earth resources while increasing their emissions to the environment which will adversely affect the quality of life. Aside from increased energy consumption, the cost of operation in the data center will also be high therefore efforts should focus on optimizing performance to ensure that quality of service while realizing gains from the services provided.

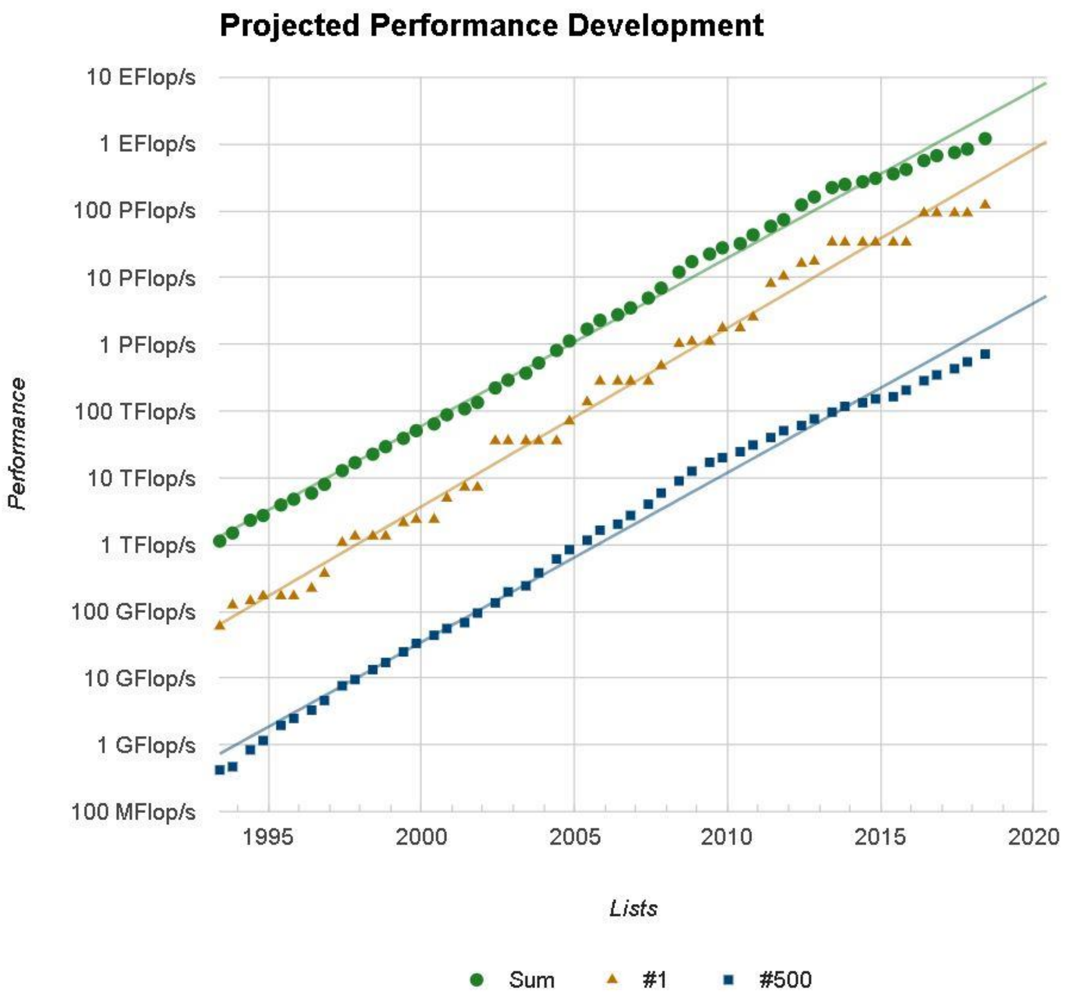


**Figure 2. Exponential Growth of Supercomputing Power as recorded by the TOP500 List**

There are many data center metrics which can be classified under Energy efficiency, Materials, Cooling, Carbon, Green, Recycling, Water, Financial Impact categories. Despite having over 137 metrics, Power Usage Effectiveness (PUE) is the most commonly used metric to assess data center performance [10]. The PUE by itself does not give an overview of performance on all other categories since it focuses mainly on energy usage, therefore data centers assessing their performance using this metric alone will most likely focus on just improving energy  through energy efficiency practices and neglect the other important aspects that are should be considered during evaluations.

When user or customers want to choose between items, comparison between the items is necessary in order to make an objective judgement. Data center benchmarking between similar data centers provides guidance to IT experts and decision makers on areas that need improvement in order to stay competitive and also to plan for future scaling [11]. The Green Grid, a not-for-profit organization provides standards and metrics that can be used in the assessment of data centers  so as to optimize performance, energy efficiency and resource utilization.

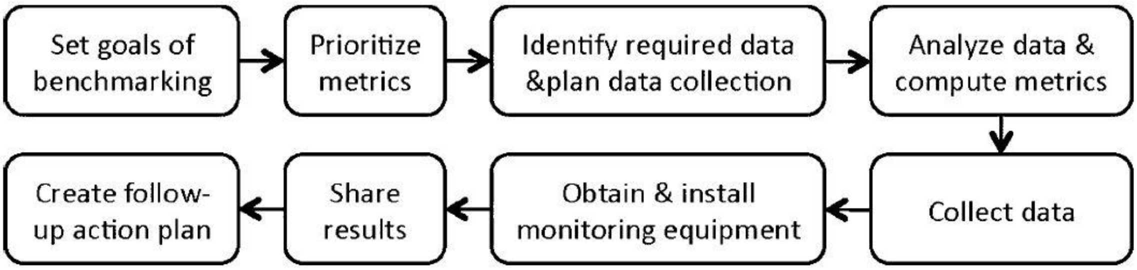


**Figure 3. Data Center Benchmarking**

Some studies have proposed some self-benchmarking solutions with metrics, standards and actions that data centers can adopt when making comparison assessments. This includes the following steps as highlighted in figure 3 [12] above:

- Identifying the goal that is to be achieved in the comparison of the data centers by detailing the scope to which systems and facilities are to be assessed.
- Prioritizing metrics which means that not all metrics are taken into consideration during the assessment based on the outlined goal and availability of resources
- Identifying the required data regarding the data centers to be compared and gathering all the relevant information. This includes the frequency of measurement and identifying the people responsible for collecting this data.
- Computing the data center metrics and performing an analysis and evaluation on the data collected.
- Collecting all the relevant data from the computation and doing consistency check to ensure that the data collected is valid and is of good quality.

- Continuous monitoring of performance of IT equipment by making comparisons in order to provide a conclusive report of areas that need improvement and for future growth and scaling.
- Gathering and sharing results with the relevant entities who in this case are other data centers that are being compared against. All the relevant results are then stored in a database for historical information
- Providing feedback and recommendations for continuous improvement of the data center.

The challenge with the above proposed methodology is that it does not take into consideration all the data center metrics. It only prioritizes specific metrics for analysis such as energy efficiency, cooling, air and thermal management and electrical power chain metrics which do not cover other aspects such as emissions, recycling, security, financials among others. This is not able to give a global view of performance and therefore It experts and key decision makes will make decisions that are not concrete regarding performance and future planning of operations in the data center.

Data centers greatly contribute to Carbon emissions because of their high energy consumption and use of inefficient cooling techniques, the biggest issues facing IT organizations today. Efficient data centers are able to better manage increased demands in computing, network and storage, lower energy costs, reduce total cost of ownership while remaining competitive and sustainable. Data centers have been making attempts to be Green by creating an awareness in reduction of energy consumption, efforts to save energy, reduce emissions so as to reduce their environmental footprint and reusing or recycling or resources by optimizing their IT equipment performance and incorporating energy efficiency equipment. This alone is not sufficient to ensure sustainable performance and behavior. Therefore by providing a means in which data centers can compete amongst themselves

Despite most data center objectives being able to provide quality services to its customers following the stipulated Service Level Agreements (SLAs) through increased performance of IT equipment and services [13], which are pivotal for increased business in the data center, the owners and operators are faced with a challenge or cost implications of sacrificing data center's performance in order to be sustainable. This is because as they strive to improve the performance of their systems then, their energy consumption increase in equal measure which implies increased usage of resource, more costs for operation and increased emissions into the environment which are harmful to the well-being of the society and reduce their quality of life.

Data centers are often have to guarantee increased computing performance to their customers which comes with a high cost for instance, in order to guarantee high performance of services there has to be redundancy which creates additional costs for the data center. Depending on the nature of service being provided, then operators are required to provide high availability and reliability of services to customers, that is, ensuring that downtimes [14] and failures are quickly resolved and customers are provided with a smooth access of services.  Recent studies have shown that on average the data center has a downtime of between 1 to 2 hours per incident reported. This can result in high costs of more than $7,900 per minute [3]. Therefore, the overall goal of data centers is to ensure they are operational during the specified period of time to minimize losses, business disruptions, loss of productivity while at the same time optimizing energy consumption.

ICT has significantly contributed to improved quality of life and hence it's optimization with environmental considerations is necessary for continued benefits to humanity. Nature, a mature economy has for years implemented strategies that have ensured a harmonious coexistence of organisms in the ecosystem. Nature knows how to survive on the planet, it knows what works, what is appropriate and what lasts on earth. There is a lot of inspiration that industries can learn from nature to help reverse the damage on the environment. Janine Benyus in her book "Biomimicry: Innovation inspired by Nature" proposes ten rules of a mature system (nature) for conducting business, which this research will translate to ICT metrics for monitoring ICT sustainability. "Economies are like ecosystems (page 242) [4]," they both make use of raw materials and energy to make products but the only difference is that, economies follow a linear transformation while nature is circular as shown in figure 4 [15].

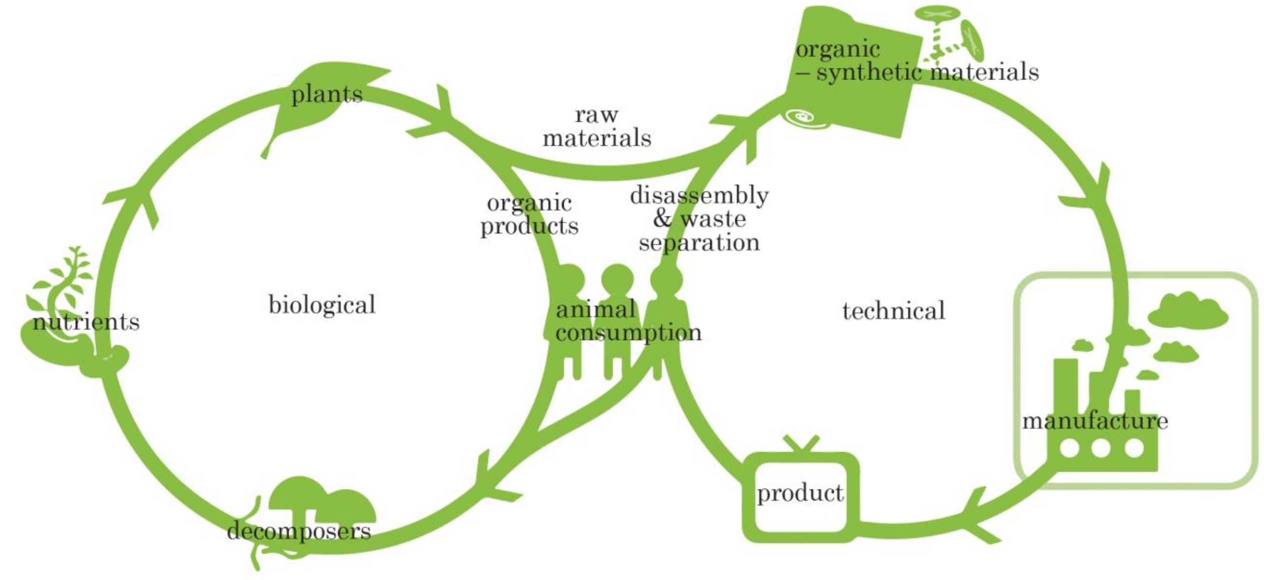


**Figure 4. Circular Economy - Cradle to Cradle**

## 2.1 Nature Metrics (Biomimicry Laws)

Nature's dense unified connections and self-regulating feedback mechanisms provides simple solutions to complex problems that would be difficult to resolve with classical computing approaches. Organisms in a mature ecosystem are self-optimized and decentralized with each organism contributing towards the overall performance behavior of the system [4]. This study proposes an adoption of nature's strategies to create a complex and harmonious data center ecosystem.

The ten rules of a for determining a data center's sustainability are:

*Use waste as a resource*: Data centers use resources such as energy, materials throughout their lifecycle and accumulate waste heat and decommissioned electronics and electrical equipment (EEE) which leave the facility as toxic waste to the environment or end up in landfills. Waste heat can be captured and used to heat buildings close to the data center [16], grey water can be cleaned and used for cooling, and decommissioned EEE should be safely dismantled for recovery of parts that can be reused [17].

*Diversify and cooperate to fully use the habitat*: ICT systems should be built on each other's strength and create a stronger alliance where common labelling and standardization allows for reuse of parts in heterogeneous systems. The assortment of energy mix into data centers especially in using alternative sources of energy which is clean reduces harmful emissions to the environment. Nature's complex ecosystem has a strong synergy and coalition which achieves less waste while increasing performance.

*Gather and use energy efficiently*: Data centers should develop mechanisms that ensure low consumption of energy by monitoring the system's energy use and also through acquisition of devices that are energy efficient and can conserve energy. Data center cooling which guarantees ideal operation of IT equipment utilizes 35 to 40 percent of energy therefore, mechanical cooling should be optimized and different solutions to cooling such as free cooling and evaporative cooling considered [18].

*Optimize rather than maximize*: Data centers should focus on providing quality services and efficiency as opposed to amassing a larger client base. Data centers should be adaptive and capable of reusing components rather than purchasing of new components and upgrades while maintaining improved quality of service. Optimization reduces resource maximal usage by providing systems that are designed and built for longevity with minimal maintenance and scheduled repairs. Devices should be easily disassembled for reuse or refurbished at their end of life [17].

*Use materials sparingly*: Nature builds for durability with minimal usage of materials [4]. Data centers should provide services such as virtualization, cloud computing where the service provider focuses on reliable quality systems that are easy to repair and upgrade while guaranteeing quality of service.

*Don't foul their nests*: Data centers should make efforts to reduce harmful emissions into the environment. Establishing data centers near energy sources reduce the emissions and losses that occur during transmission and distribution. Pollution from the facility to water sources such as rivers might lead to death of organisms and affect the health of the society. Decentralizing of data center services and resources to local geographical areas reduced the emissions that would occur when the same services are sourced from far of locations. Data centers policies should prohibit pollution of resources such as water, air and focus on energy efficiency of IT equipment.

*Don't draw down resources*: Nature curbs excess from within [4]. It does not use nonrenewable resources faster than it can find alternatives and at the same time it does not use renewable resources and energy faster than it can recreate. Data centers need to minimize their resources consumption to avoid depletion of earth resources which will deprive our future generations.

*Remain in balance with the biosphere*: Data centers need to continually monitor and control emissions into the environment by designing self-regulating systems that can adjust accordingly to ensure that they do not harm the environment [4]. Smart sensors can be embedded in devices and systems such as cooling systems help monitor their performance and adjust any anomalies such as harmful emissions to the ecosystem.

*Run on information*: The objective of evaluating data centers performance is to establish feedback channels of the interactions of components within and outside of the facility. This mitigates faults within the system, creates resilience and recovery in cases of disasters or system failure. The importance of running on information sensitizes customers on choosing services and data centers which are certified as eco-friendly creating a community that is cautious of what it consumes [17].

*Shop locally*: Data centers need to source for resources closer to their locations to reduce the energy and emissions. Waste energy should be channeled to nearby buildings for heating, adoption of free cooling from the locally available air can substitute mechanical cooling and use of renewable energy taken into consideration [19]. The use of local expertise creates a reliable, self-sufficient ecosystem.

ICT systems contribute to the exhaustion of finite earth resources and harmful pollution into the environment. Nature's evolution depicts that ecosystems have two phases: developing phase where they are unstable but highly productive and mature phase where systems are more complex, diversified and stable. ICT systems should be designed as mature systems in order to combat the effects on the environment. Biomimicry's ten laws have been used to design green network solutions with provision of metrics that compare different network solutions and make selection of the ideal solution easier for users [20].

## 2.2 Data Center Metrics Dimensions

The amount of data center metrics that exist provide a hard task when assessing data centers performance to provide an extensive analysis. This study aims at simplifying the metrics evaluation process using the Biomimicry laws. Table I highlights metrics from diverse dimensions to comprehensively include all factors that contribute to the sustainability of the data center.

The data center metrics are categorized into the following categories: Energy efficiency, Materials, Cooling (Traditional, chilled water and Air), Carbon, Green, Recycling (Energy and Materials), IT Performance (Networks, Storage and Security) and Financial Impact [3].

Energy efficiency of the system's overall useful work done in comparison to the energy consumed. Materials category which analyses IT equipment efficiency. Cooling of the data center's system is to guarantee optimal performance of IT equipment. Data center cooling uses different cooling technologies: mechanical, chilled and air cooling. The Carbon dimension focuses only on emissions to the environment while the Green category evaluates the amount of data center energy that is from clean sources.

Recycling highlights waste resource utilization efficiency of energy and materials in the data center. IT Performance ensures that the data systems are effective while executing tasks. Water is an important resource for consideration when designing, identifying ideal location for a data center and in the day to day operations inside the data center. However, it should be adequately utilized hence the need to evaluate water usage in data centers.

In addition, increased resource utilization can contribute to high energy costs and maintenance of IT equipment; therefore, the organization should manage its Financial performance to realize gains from the data center. In all the categories, the objective of the data center metrics is to either maximize or minimize for efficiency.

The monitoring and measurement of ICT solutions help provide reliable and optimized services to customers who are the main beneficiaries for improved well-being and quality of life, while ensuring that designs of systems is sustainable focusing on the environment, economics and social factors [13].

## 2.3 Frameworks that Assess Data Centers Performance

There has been significant research on performance evaluation of data centers and cloud computing [21] with most studies focusing on metrics identification, however, they do not provide detailed analysis of all the metrics. The frequently used metric in data center performance assessment is PUE [10] is limited in terms of providing a holistic view and therefore should not be single-handedly used to evaluate data center performance.

A scorecard framework had been proposed that analyzes the data center's performance in the following sub-dimensions productivity, operations, efficiency, sustainability and risks such as location and infrastructure as shown in figure 5 and by using probabilities and time dependencies to provide at a general score of the data center's performance. The challenge with this model is that it does not conclusively detail how to use the tool in evaluations and is also not exhaustive of all the data center dimensions therefore cannot provide a good overview for comparison [21].


**Figure 5. Data Center Scorecard**

There has also been a proposal to use simple algorithms of calculating data center energy savings over a period of time and thereafter, assessing performance of IT equipment in terms of energy consumption [22]. This presents a challenge in that it is difficult to determine the useful life of IT equipment and also the complexities brought about by varying energy use by equipment and business demands. As technology advances and new upgrades are available for IT equipment and the need to acquire better performing equipment, then this model faces complexities of having equipment for shorted periods of time which makes measurements over a long time very difficult. Data centers also take longer to fully deploy equipment for their business operations therefore this makes this approach not feasible for evaluating performance. It also solely focuses on energy efficiency and savings and does not incorporate other dimensions important for data center evaluations and comparison.

Existing models have been proposed for cloud selection, by locating data centers closer to the demands of users for internet, network, storage among other needs to ensure that high response times and reduced costs of operations of transport and distribution. Several factors influence the selection of cloud computing locations such as energy sources, the price of land, electricity costs, demand for services, availability of expertise and also the environmental temperature in the region which is important for cooling of IT equipment considerations. The Mixed Integer Linear Programming model [23] provides and efficient mechanism of selecting data center location taking into consideration the costs associated with establishing the data center, demands for services while ensuring that operations are optimized to guarantee performance efficiency while minimizing the amount of energy used.

A telecommunications company (IranCell) in Iran, has proposed the adoption of hybrid multi-criteria decision making model for ranking data center using SWARA and VIKOR [24], where SWARA was utilized to calculate the weights of the identified criteria and sub-criteria and VIKOR used to rank the cloud service providers. The criteria and sub-criteria identified focused on the Quality of Service (QoS) evaluation of services to users. This assessment was carried out in order to provide managers and key decision makers with guidelines on their data centers performance as well as ways in which performance can be improved given the available resources.

The use of multi-attribute group decision-making (MAGDM) [25] based on scientific principles help organizations decide on which cloud service provider is suitable for their business needs in a comprehensive manner by analyzing both objective factors such as cost and subjective factors such as Technology, Organization and Environment (TOE) [26]. The challenge is that data centers have different functions such as Accounting, Administration Information Technology among other who all together contribute towards the decision-making process. Therefore, for experts who are not technology savvy, it will always be a problem trying to make meaning from such analysis.

Efficient resource utilization is an important objective in cloud computing and operations of data centers. Cloud customers and user preference are for services that are reliable, flexible, dynamic and efficient therefor effective resource allocation strategies have to be adopted that are able to predict user resource requirements and allocate resources accordingly. Resources such as virtualization, service classification can be complex to adequately provision, therefore Data Envelopment Analysis (DEA) [27] has been proposed to help solve this imbalance using the cloud parameters in order to provide the most suitable solution for users and vendors.

Resource demands and tasks scheduling for efficiency is a big problem in cloud computing. Different business have varying demands for resources which differ over time therefore the challenge of achieving high performance while meeting the Service Level Agreements can greatly influence improvements in balancing of resources, reliability, and cost reductions of operations in the data center while reducing energy consumption in the data center. A proposed model based on multi-objective genetic algorithm (MO-GA) [28] using CloudSim has been able to compare existing methodologies for task scheduling and obtained better results by providing efficiency of performance on multiple data center operations.

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The frameworks discussed here have a challenge in that they do not extensively analyze all components that make up a data center as highlighted in table 1, rather they focus on different aspects of a data center's performance such as resource allocation, site selection, tasks scheduling, energy savings, ranking using score cards. This creates a gap that can be resolved by providing a granular representation of the all the components that make up the data center evaluation to avert fatalities and risks that might occur when all dimensions are not considered. The simplification of the decision making process using Biomimicry laws provides key decision makers such as financial accountants, managers who most of the times are not IT professionals with an understandable analysis of the global performance of the data center and reduce the over reliance on IT experts.

**Table 1. Data Center Performance Comparison Frameworks**

| Assessment Frameworks | Data Center Metrics Dimensions | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Energy | Material | Cooling | Carbon | Green | Recycling | IT Performance | Financial |
| Data Center Scorecard | √ | | √ | √ | √ | | √ | |
| Simple Algorithms | √ | | | | | | | √ |
| Cloud Selection (MILP) | √ | | √ | | | | √ | |
| Cloud Service Provider (Irancell) | | | | | | | √ | |
| Cloud Service Provider (MAGDM) | | | √ | | | | √ | √ |
| Cloud Computing (Resource Usage) | | | | | | | √ | |
| Cloud Computing (MO-GA) | √ | | | | | | √ | √ |

# 3 METHODOLOGY

The research methodology was adopted to systematically answer the research questions and objectives of the study [29]. The outlined methodology phases in figure 6 below were chronologically followed to carry out this thesis research. This followed the principles applied in research methodology in order to achieve quality assurance of the data collected and analysis of the computations.

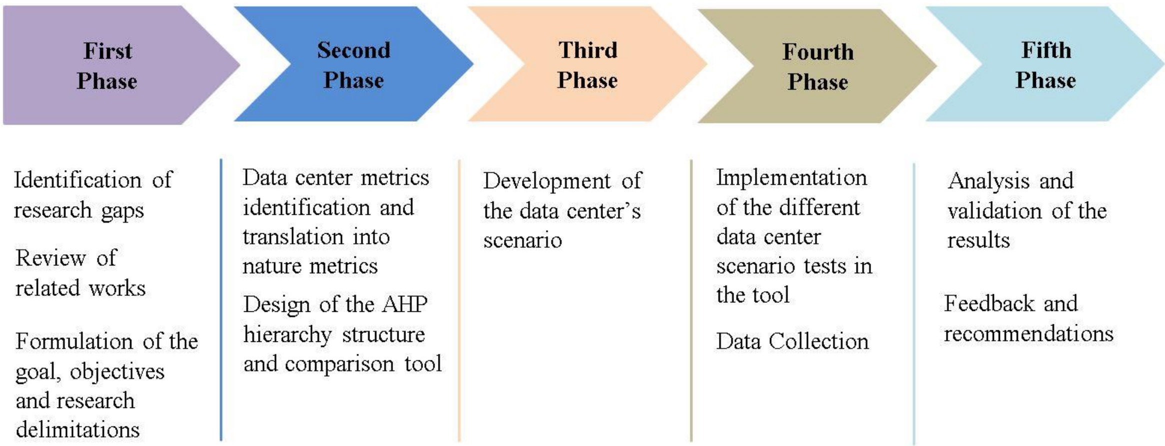


**Figure 6. Research Methodology**

The first phase focused on identified the research gaps and reviewing existing works that focus on data center performance comparison frameworks to identify the extent to which the frameworks assess data centers efficiency. This also included defining the objectives of the research focusing on the goal of the study, formulating research objectives and questions as well as identifying the delimitations of the study.

In the second phase, we identified all the existing data center metrics from different sources focusing on the different aspects of a data center's efficiency and thereafter translating them into nature metrics (10 Biomimicry laws) by assessing their positive and negative impact on the environment and assigning a weight following AHP measurement scale. Thereafter, we designed the comparison tool using Analytic Hierarchy Process.

The third phase focused on the development of the data centers scenario by focusing on data centers performance in France, Sweden and Germany then using different factors such as each country's Energy technology and distribution, Energy Water Intensity Factor (EWIF) [8] which is the amount of water used in the production of each energy technology, and the global emission factor for each kind of energy technology.

In the fourth phase we focused on testing different experiments using data center metrics in the comparison tool and thereafter, collecting the final ranking data for both the nature metrics and the global ranking.

Finally in the fifth phase, the data collected was analyzed, validated and appropriate recommendations and feedback provided could be visibly seen from the data representations.

## 3.1 Data Center Metrics

Data center metrics evaluate energy efficiency to determine the useful work done relative to the energy used. Power Usage Effectiveness (PUE) [10] focuses on the power usage of IT equipment compared to the power supplied by the data center while Partial Power Usage Effectiveness (pPUE) [10] considers a section of the data center especially for data centers collocated with offices. Data Center Energy Productivity (DCeP) computes the useful work done in comparison to the energy used which is beneficial for gains analysis. Green Energy Coefficient (GEC) calculates clean energy being used in the data center while Data Center Infrastructure Efficiency (DCiE) [30] compares data center energy efficiency with other data centers. Water Usage Effectiveness (WUE) and Water Usage Effectiveness source (WUEsrc) focus on the amount of water used in the data center and for power generation supplied to the data center.

Data center cooling is essential for optimal operation of IT equipment however, it uses approximately 35 to 40 percent of the total power expended in the data center [31]. Therefore, the Coefficient of Performance (COP) examines efficiency of the cooling system by determining the power used compared to the power input. Air Economizer Utilization Factor (AEUF) assess the extent to which air-side economizer is used for cooling throughout the year.

The emissions from the data center to the environment affect the well-being of the society and other living organisms. A green data center ensures optimal operations with reduced emissions. The Carbon usage Effectiveness (CUE) evaluates the Carbon emissions from the data center into the environment to provide information on areas of improvement. Energy Reuse Factor (ERF) and Energy Reuse Efficiency (ERE) [32] analyses the efficient reuse of energy from the data center to nearby offices or buildings. Electronics Disposal Efficiency (EDE) [17] checks the disposal process of electronics and equipment to ensure that there is responsible reuse, recycling and disposal.

The performance of a data center is imperative for enhancements and planning of future loads. Data Center Energy and Productivity Index (DEEPI) and Flops per Watt (FpW) considers the productivity of the data center to energy consumed and server performance respectively. The appraisal of the Response Time (RT) [33] and Throughput determines the time it takes to perform an operation and data transfer from the storage system. The nature of data kept in the data center means that security must be guaranteed, and this also includes natural disasters, thus Connection Establishment Rate (CER) determines the time it takes to establish a three-way handshake connection.

Air and thermal management metrics such as Data Center Temperature ensure that the facility maintains the recommended ASHRAE temperature to avoid damage to the IT equipment while the Rack Cooling Index (RCI) check the environmental status of the data center to ensure optimum operation of the rack servers. Data center’s network is core for applications and operations. Inadequate outages can cause significant data and revenue losses. Network utilization (Unet) checks the bandwidth used in relation to the available capacity while Network Traffic per kilowatt-hour (Net Traffic) determines the efficiency of the network equipment in data transfer compared to the energy used. The Return on Investment (ROI) [3] provide important financial performance integral for future scaling and enhancements. The different dimensions extensively contribute to the goal of a sustainable data center through adequate resource utilization, reduced waste and hazardous emissions to the environment while achieving economic viability. Table 2 describes the above highlighted metrics with their formulas and objectives of performance.

**Table 2. Metrics Description**

| Metric | Definition | Formula | Objective |
|---|---|---|---|
| PUE | Total facility power to IT equipment power | $\frac{Total\ Facility\ Power}{IT\ Equipment\ Power}$ | Minimize |
| pPUE | Considers a section of the data center | $\frac{Total\ Power\ in\ a\ section\ of\ the\ Data\ center}{Total\ Power\ of\ the\ IT\ Equipment\ Section}$ | Minimize |
| DCeP | Useful work done to energy used | $\frac{Useful\ Work}{Total\ Facility\ Power}$ | Maximize |
| GEC | Clean energy used in the data center | $\frac{Green\ Energy\ Used\ in\ the\ Data\ Center}{Total\ Data\ Center\ Source\ Energy}$ | Maximize |
| DCiE | Data centers energy comparison | $\frac{IT\ Equipment\ Power}{Total\ Facility\ Power}$ | Maximize |
| COP | Power input to power output of the system | $\frac{Power\ Output}{Power\ Input}$ | Maximize |
| AEUF | Extent of air-economizer usage | $\frac{Air\ Economizer\ Hours\ in\ Full\ Cooling}{8760} x\ 100$ | Maximize |
| CUE | Carbon emissions from the data center | $\frac{Total\ CO2\ Emissions}{IT\ Equipment\ Energy}$ | Minimize |
| ERF | Percentage of waste energy that is reused | $\frac{Reuse\ Energy}{Total\ Energy}$ | Maximize |
| ERE | Efficient reuse if energy from the data center | $(1 - ERF) x PUE$ | Minimize |
| EDE | Disposal process of decommissioned EEE | $\frac{Weight_{Responsibly\ Disposed}}{Total_{Weight\ Disposed}}$ | Maximize |
| WUE | Water used for cooling in the data center | $\frac{Annual\ Water\ Usage}{IT\ Equipment\ Energy}$ | Minimize |
| WUEsrc | Water used for power generation and onsite | $(EWIF + PUE)\frac{Annual\ Site\ Water\ Usage}{IT\ Equipment\ Energy}$ | Minimize |
| DEEPI | Data center productivity per watt | $(IT - PEW) x (SI - EER)$ | Maximize |
| FpW | Benchmarking servers performance | $\frac{Floating\ Points\ Operations}{Joules}$ | Maximize |
| RT | Time to complete a read or write operation | Ideal latency value is 0 | Minimize |
| Throughput | Speed of data delivery in storage system | $\frac{Megabytes\ moved\ per\ second}{Watt}$ | Maximize |
| CER | Speed of connection establishment | Application and policies in firewall dependent | Maximize |
| RCI | Health status of the thermal environment | Ideal is 100% | Maximize |
| Unet | Bandwidth used to available bandwidth | Maximum achievable is 80% | Maximize |
| Net Traffic | Outbound bits over data center energy used | $\frac{Outbound\ Bits}{Data\ Center\ Energy}$ | Maximize |
| ROI | Monetary value of investments | $\frac{Net\ Profit}{Cost\ of\ Investment} x100$ | Maximize |
| Temperature | ASHRAE recommended temperatures | Recommended value 18-27°C | Optimize |
| CNEE | Efficiency of packet delivery process | $\frac{Power\ Consumed\ by\ Network\ Equipment}{Effective\ Network\ Throughput\ Capacity}$ | Minimize |

## 3.2 Metrics Rules Definition

The assessment of the data center metrics and nature metrics are weighted using the Saaty scale [6] with the impact of each law classified as indicated in table 3. To determine the impact of each law, expert judgement and analysis is required in order to classify each law accordingly. Thereafter the positive impacts (benefits) and negative impacts (costs) of each metric on the environment are outlined in the UMLs.

**Table 3. Saaty Scale**

| Numerical Value | Definition |
|---|---|
| / | Low importance |
| 3 | Slightly more important |
| 5 | Moderately important |
| 9 | Strong importance |

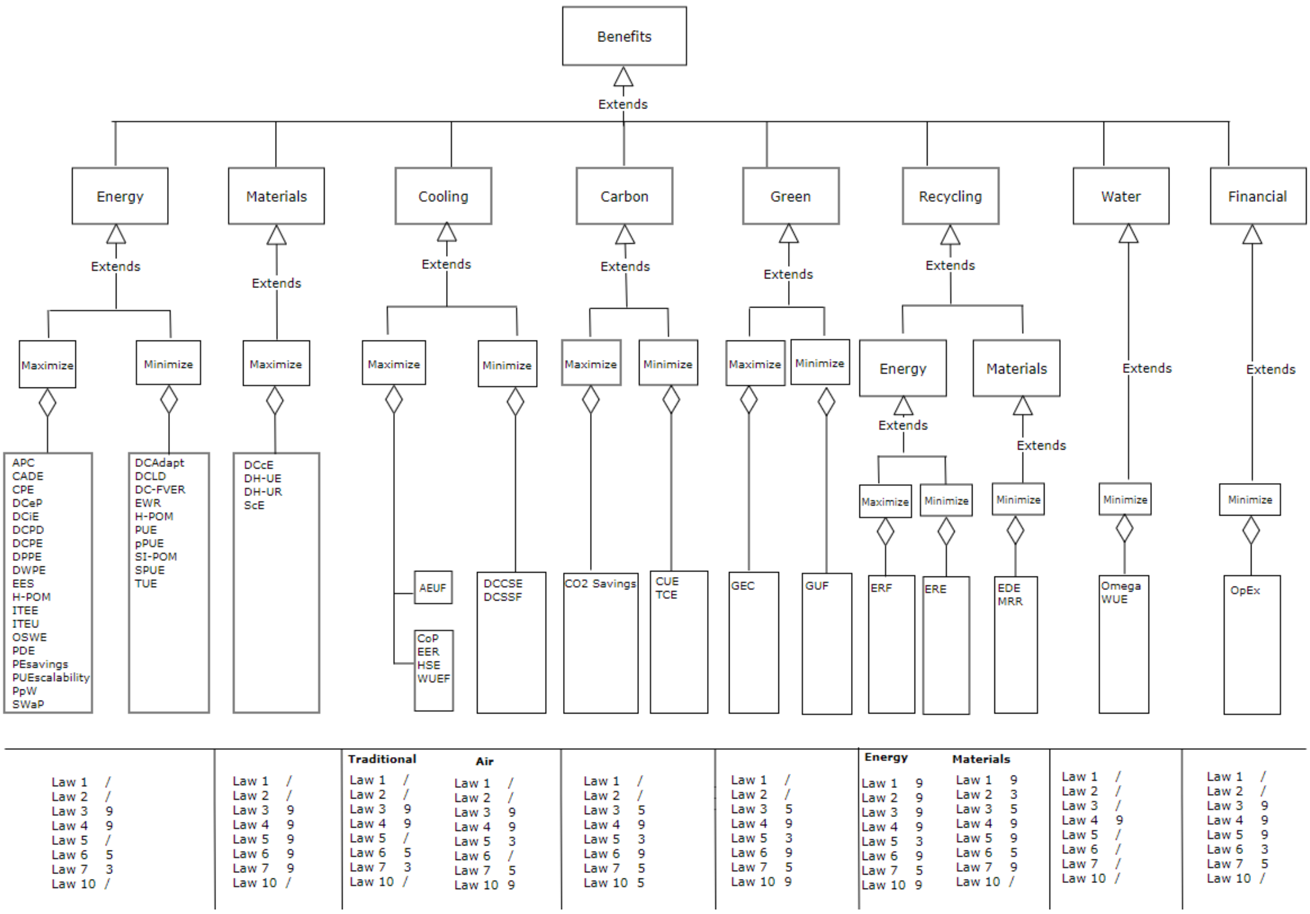


**Figure 7. Benefits UML**

The benefits UML in figure 8 show each data center metrics dimension by highlighting its positive impacts on the environment, their dependencies on specific nature metrics, the objective of each metrics which could be to maximize or minimize efficiency, their corresponding metrics and the vector analysis for each dimension.

The nature metrics (Biomimicry laws) as earlier outlined are use waste as a resource (Law 1), diversify and cooperate to fully use the habitat (Law 2), gather and use energy efficiently (Law 3), optimize rather than maximize (Law 4), use materials sparingly (Law 5), don't foul the nest (Law 6), don't draw down resources (Law 7), remain in balance with the biosphere (Law 8), run on information (Law 9) and shop locally (Law 10).

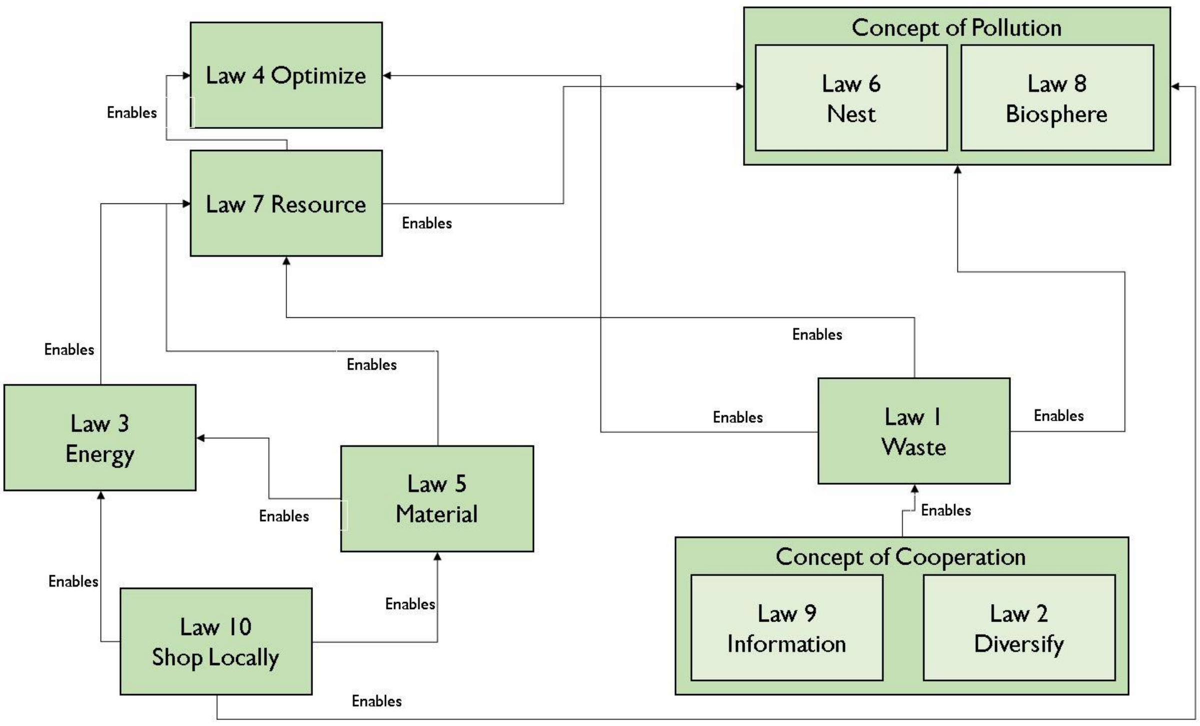


**Figure 8. Nature Metrics Relation**

To effectively understand the metrics rules definition, figure 7 depicts the relationship and dependencies between the different nature metrics (Biomimicry Laws), which is then used to determine how each data center metrics relate with the nature metrics by defining each dimension of data center metrics with its corresponding vector.

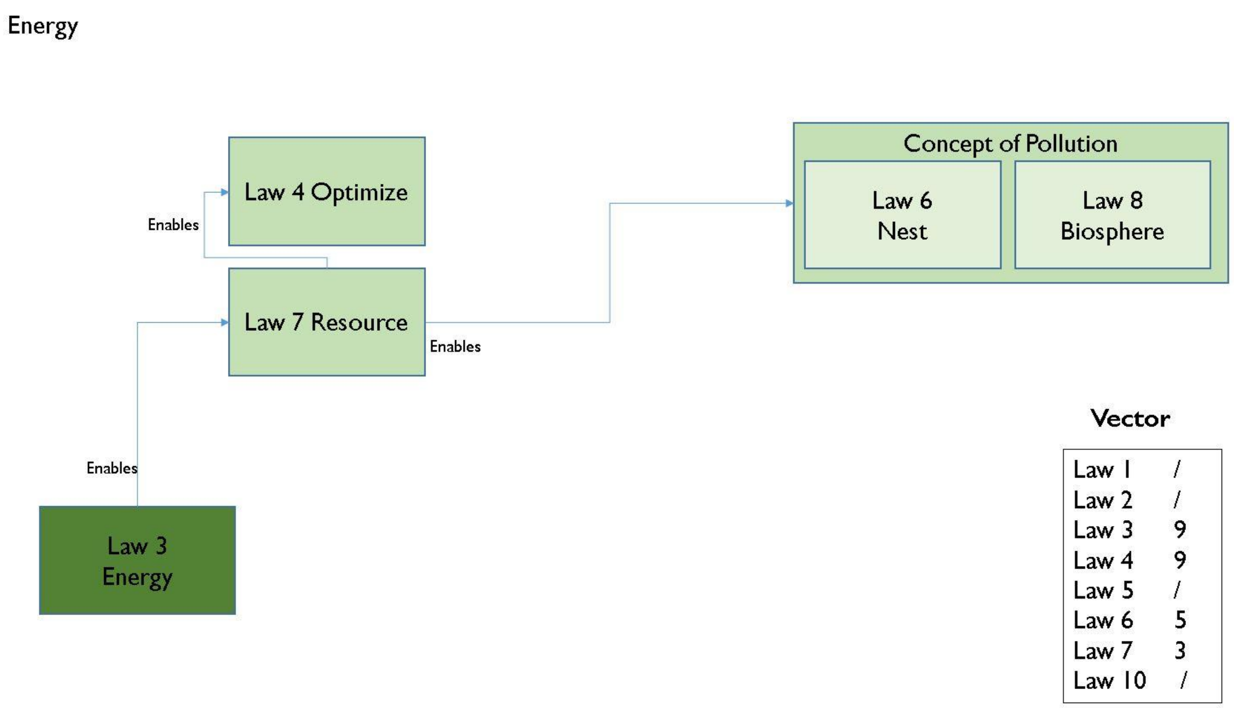


**Figure 9. Energy Relation**

The figure 9 above highlights the relationships in Energy efficiency and starting at Gather and Use energy efficiently metric (Law 3) it clearly shows how each Law relates with Law 3. This then gives Energy efficiency a vector of {/ / 9 9 / 5 3 /} which can be interpreted as follows: Law 1 and Law 2 (/) do not have an impact on energy efficiency, Law 3 and Law 4 (9) have a strong emphasis on efficient energy utilization and optimization of operations in the data center, Law 5 (/) has no impact on energy, Law 6&8 (5) implies that reduced energy use reduces pollution but is also dependent on the primary energy used in the data center, Law 7 (3) because reduced energy utilization does not necessary imply reduced resource usage and Law 10 (/) is difficult to deduce whether the primary energy is from a local source or has been transported from a different geographical region.

The figure 10 shows the relations that exist in materials which translates to a vector of {/ / 9 9 9 9 9 /} with Law 2 and Law 2 (/) having no impact on the category. Law 3, Law 4, Law 5, Law 6&8, Law 7 (9) have a strong emphasis on improved performance of equipment to achieve efficiency with reduced resource use which leads to minimal emissions on the environment. Law 10 (/) has no impact on the materials.

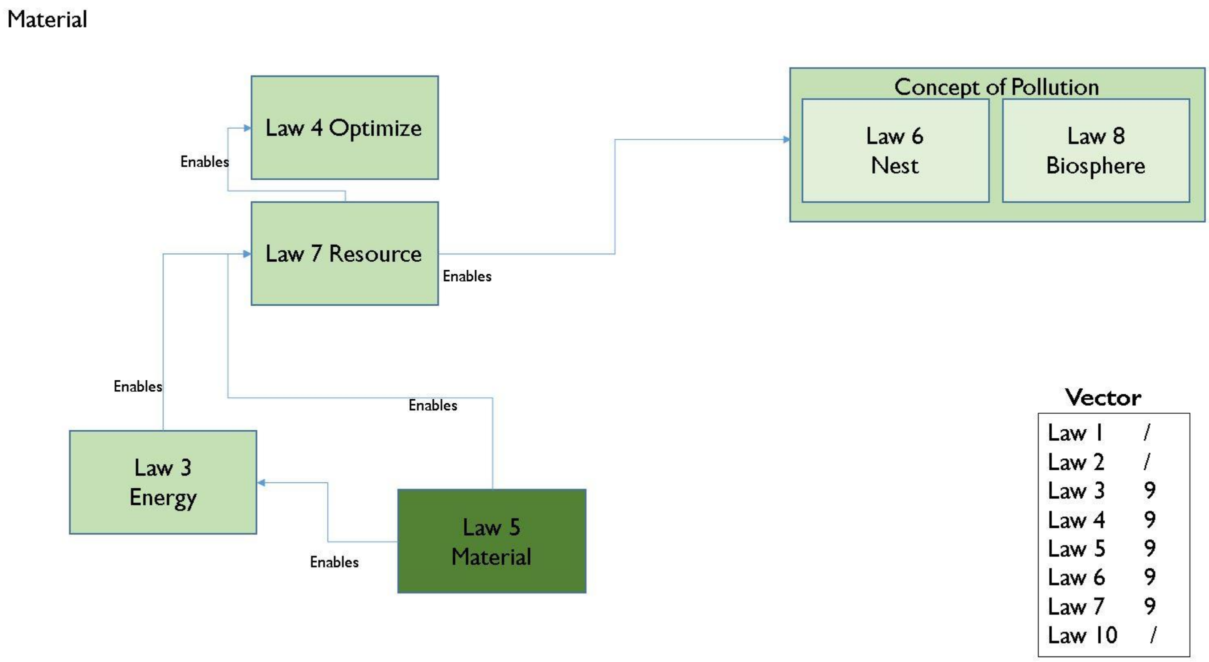


**Figure 10. Materials Relation**

Data center cooling is categorized into Traditional (mechanical) cooling and air (free) cooling in our study. Traditional cooling relation in figure 11 translates to a vector of {/ / 9 9 / 5 3 /}. Law 1 and Law 2 (/) have no impact on traditional cooling. Law 3 and Law 4 (9) have a strong impact because a big proportion of the data center energy is used to cool IT equipment (approx. 35-40% of energy) therefore optimization is necessary. Law 5 (/) has no impact, Law 6&8 (5) is because energy use for mechanical cooling has some level of pollution to the environment. Law 7 (3) is because energy is a resource used for cooling while Law 10 (/) has no impact

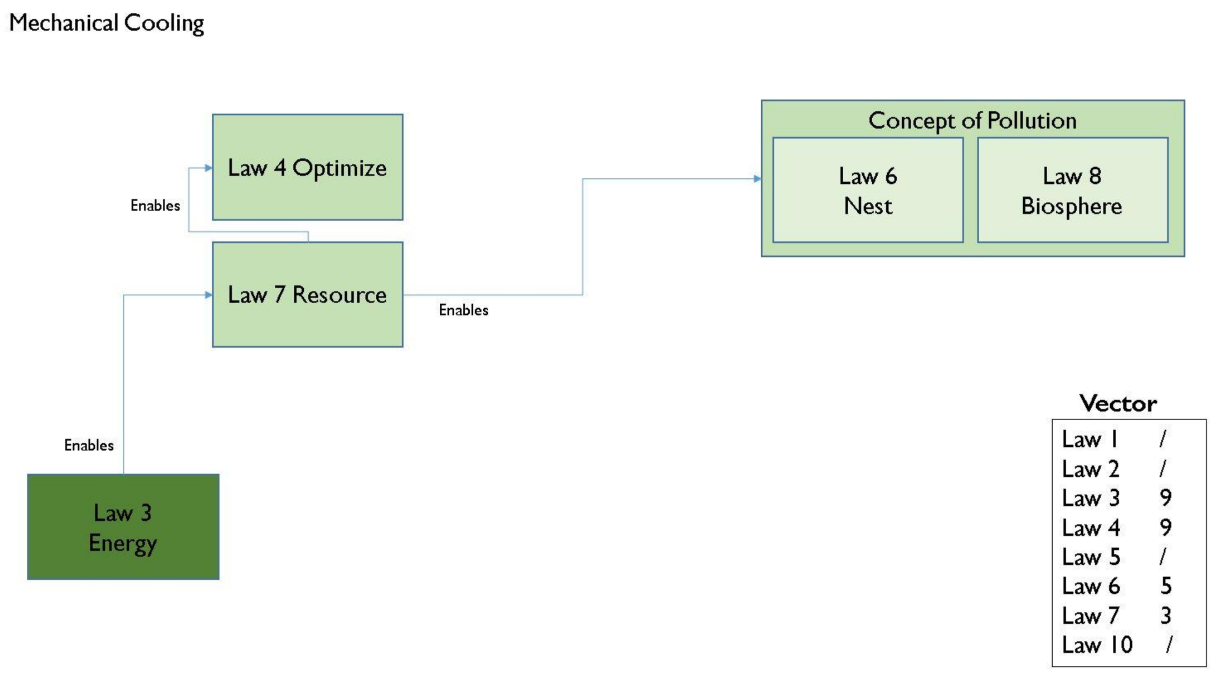


**Figure 11. Mechanical Cooling Relation**

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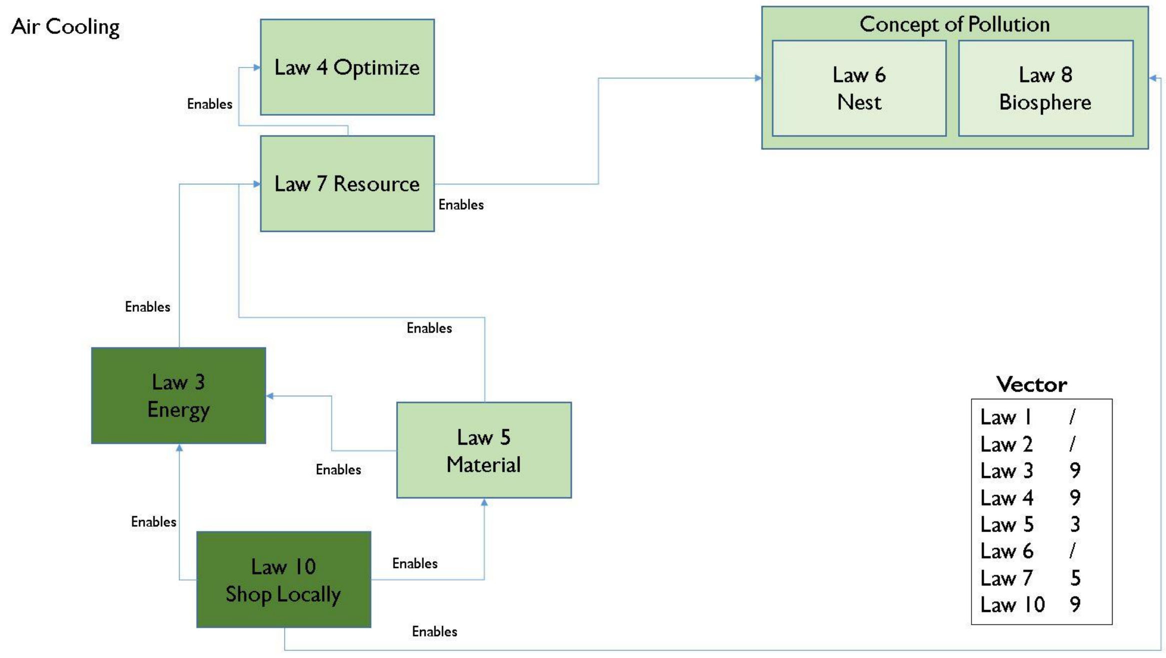


**Figure 12. Air Cooling Relation**

Air cooling makes use of the locally available free air for cooling. From the figure 12 above air cooling achieves a vector of {/ / 9 9 3 / 5 9} with Law 1 and Law 2 (/) having no impact. Law 3 and Law 4 (9) have a strong impact because using air for cooling reduces the need to use energy for cooling. Law 5 (3) means that in some areas the kind of air available especially in humid areas can reduce the reliability of the IT equipment. Law 6&8 has no impact because air reduces pollution but is also hard to conclude. Law 7 (5) implies that reduced reliability of IT equipment is costly and increases resource use and Law 10 (9) is a strong impact because the air used is locally available within the data center environs

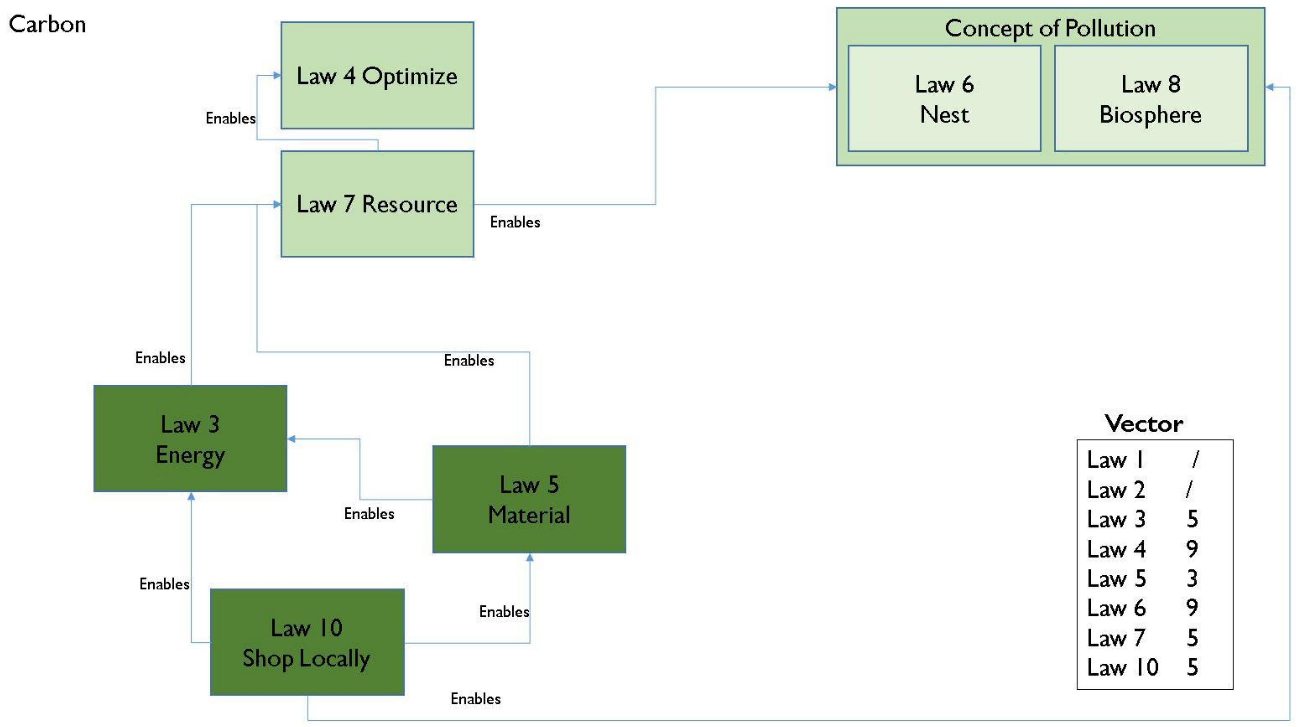


**Figure 13. Carbon Relation**

The figure 13 gives Carbon a vector of {/ / 5 9 3 9 5 5} with Law 1 and Law 2 (/) having no impact. Law 3 (5) because reduced and efficient energy usage reduces emissions into the environment. Law 4 (9) is strong because data center operations need to be optimized to reduce Carbon emissions. Law 5 (3) is because less emissions could be because of less equipment usage in the center. Law 6&8 (9) has a strong impact of reducing emissions from the data center to the environment. Law 7 (5) is because if data center uses less equipment either through virtualization and dematerialization then it will use minimal resources and Law 10 (5) is because use of locally available energy (wind, solar etc) can reduce emissions although this is dependent on the primary energy source of the data center.

The Green category has a vector of {/ / 5 9 3 9 5 9} as shown in figure 14 with Law 1 and Law 2 (/) having no impact. Law 3 (5) is because some data centers use a mix of energy (clean and not clean sources). Law 4 (9) has a strong impact of optimizing available clean energy to improve on the greenness level of the data center. Law 5 (3) minimal impact because the same equipment uses both clean energy and energy that is not clean therefore it is not easy to deduce. Law 6&8 (9) has a strong impact because clean energy has minimal emissions to the environment. Law 7 (5) is because clean energy reduces the intensive use of resources such as energy from non-renewable sources and Law 10 (9) is because clean energy is usually from locally available air, water or solar sources.

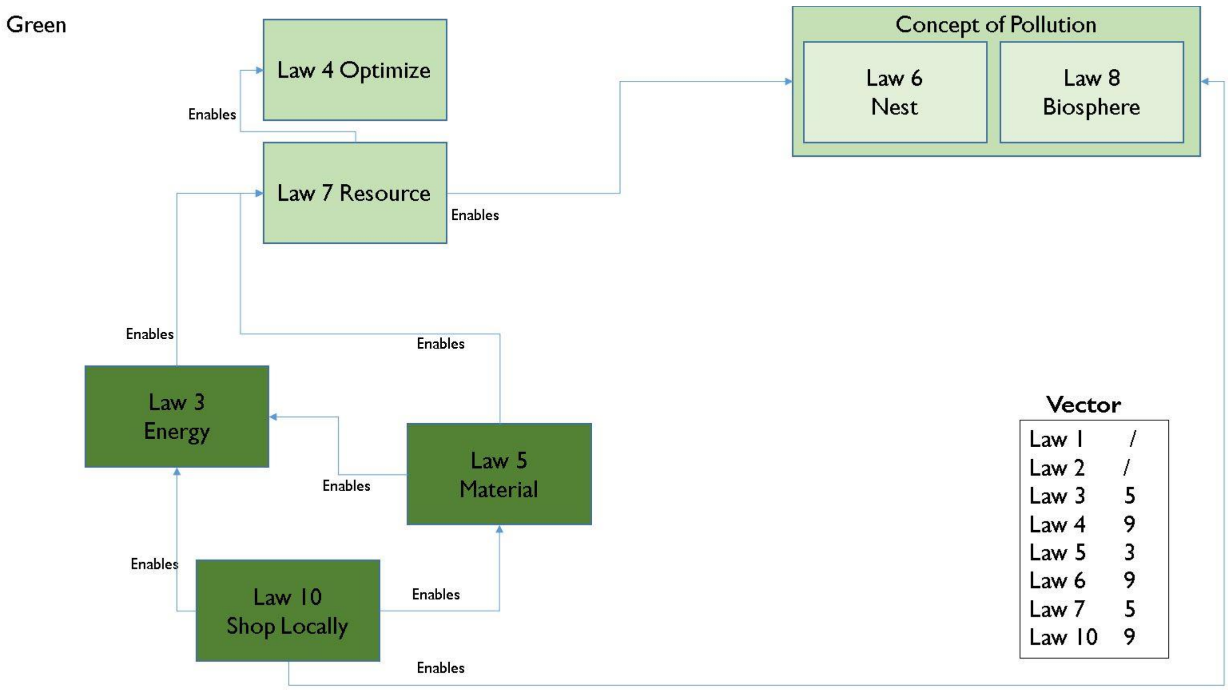


**Figure 14. Green Relation**

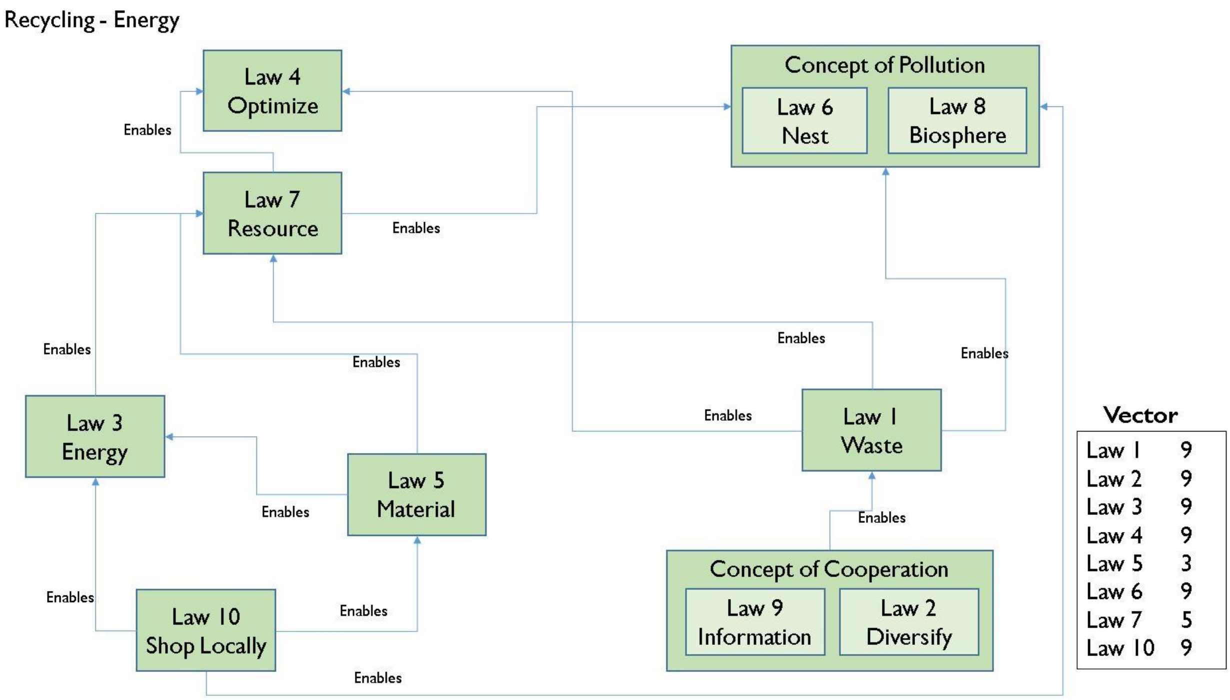


**Figure 15. Energy Recycling Relation**

Recycling can be categorized into Energy and Materials recycling. In figure 15, energy recycling has a vector of {9 9 9 9 3 9 5 9} where Law 1, Law 2, Law 3 and Law 4 (9) have a strong impact of optimal use of rejected heat to warm up buildings close to the data center which requires a cooperation and understanding of the energy needs of the neighboring buildings or industries. Law 5 (3) is because material use has minimal impact on energy reuse. Law 6&8 (9) is because reuse of heat ensures that there are no ejected harmful emissions to the environment. Law 7 (5) is because recycling of waste heat ensures reduces resource use for generating energy to heat nearby buildings and Law 10 (9) involves gathering information on energy needs from nearby buildings to ensure that waste heat is adequately utilized.

Materials recycling shown in figure 16 has a vector of {9 3 5 9 9 5 9 /}. Law 1 (9) has a strong impact on proper disposal of equipment and material at their end of life according to set environmental guidelines. Law 2 (3) materials recycling has minimal impact on the use of the habitat although device labelling and standards ensure that important components are successfully extracted for use in other devices. Law 3 (5) is because some energy will be used for extraction of parts during the disposal process. Law 4 (9), Law 5 (9), Law 7 (9) have a strong impact on efficient disposal of decommissioned electronics and electrical equipment which safeguards components extracted for use elsewhere to achieve resource efficiency. Law 6&8 (5) is because it is usually not clear how equipment is disposed, sometimes it could be to developing nations' landfills and finally Law 10 (/) has no impact.

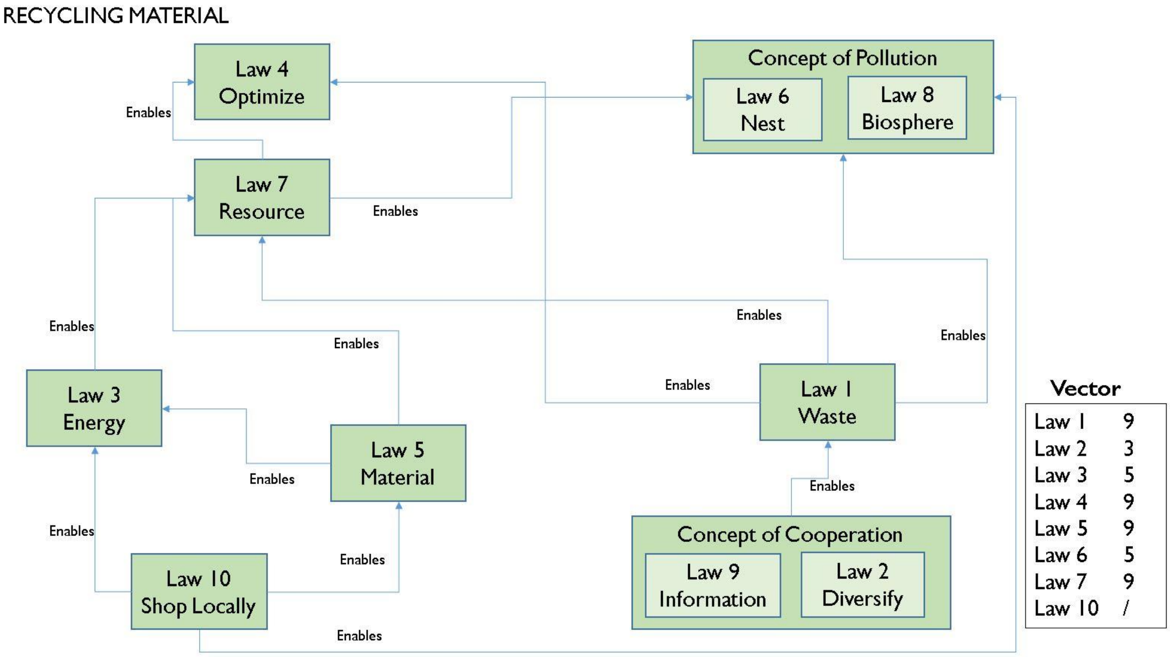


**Figure 16. Material Recycling Relation**

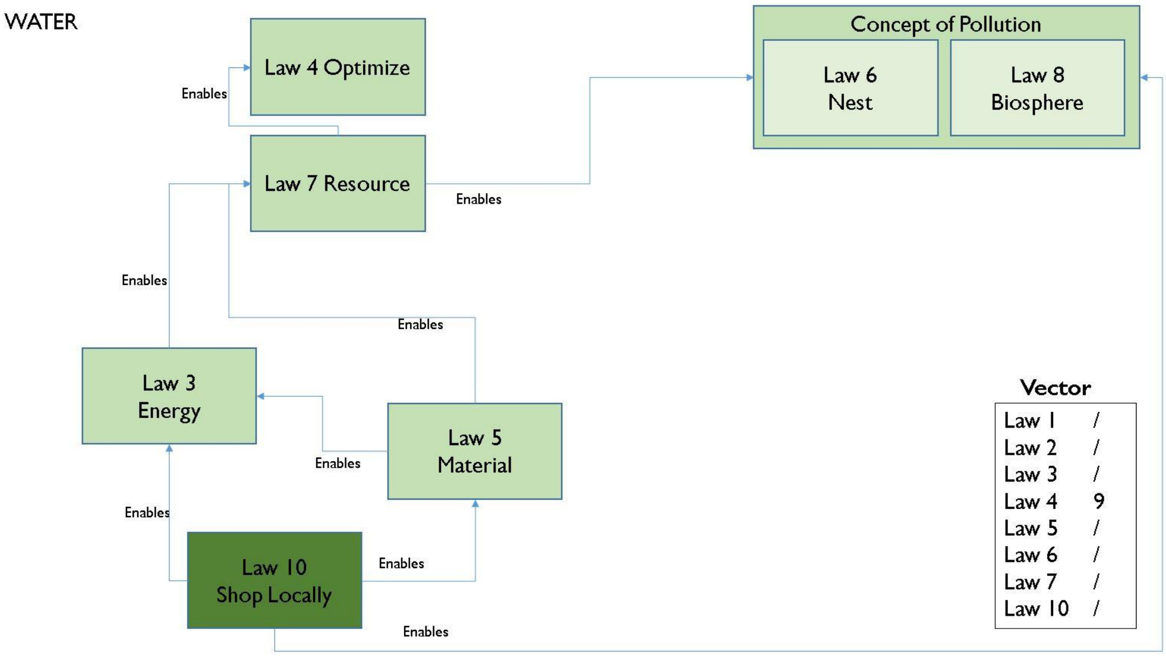


**Figure 17. Water Relation**

Water is a precious resource that should be protected. The figure 17 below shows water has a vector of {/ / / 9 / / / /} which infers that Law 1, Law 2, Law 3, Law 5, Law 6&8, Law 7 and Law 10 (/) have no impact on water while Law 4 (9) has a strong impact because even though water is a resource that is locally available it should be well utilized and optimized. This is because studies have a shown that a data center can drain an Olympic-sized pool in just 2 days.

Data center's aim at providing quality services while keeping operational costs at a minimum to realize value from their business. The financial impact shown in figure 18 gives a vector of {/ / 9 9 9 3 5 /} with Law 1 and Law 2 (/) having no impact. Law 3, Law 4 and Law 5 (9) have a strong impact because efficiency and optimization of data center activities reduces the operational costs. Law 6&8 (3) reduced operational costs do not necessarily reduce Carbon emissions especially when the energy source is non-renewable. Law 7 (5) is because reduced operational costs reduces the amount of resources used in the facility and Law 10 (/) has no impact.

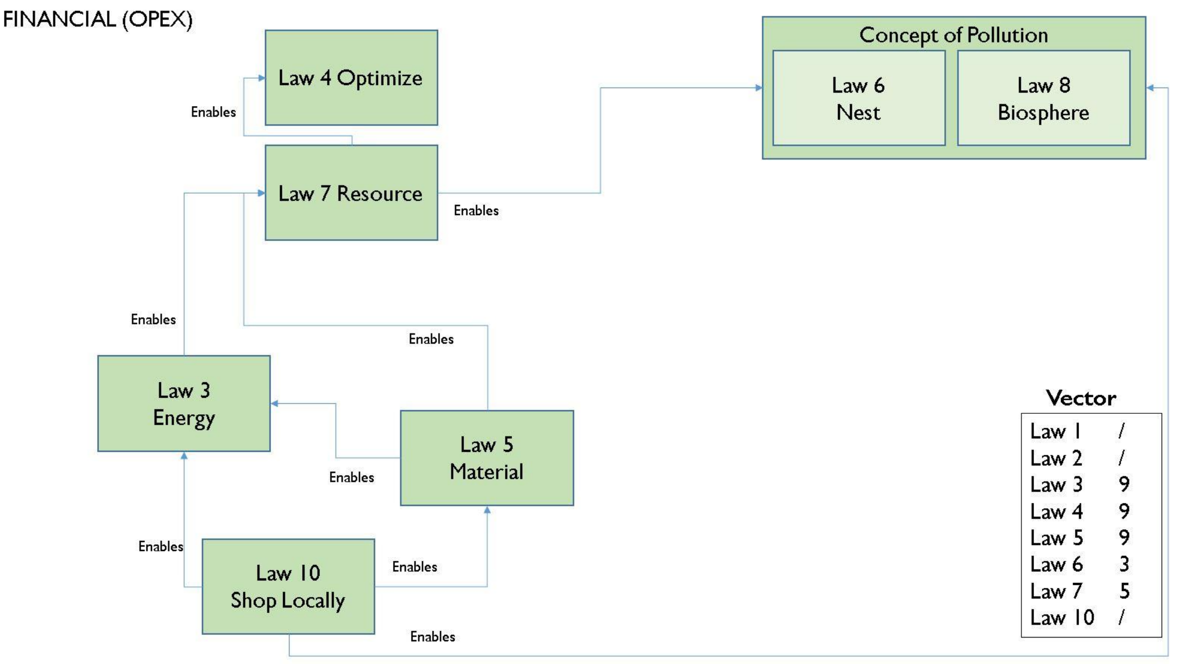


**Figure 18. Financial Impact Benefits Relation**

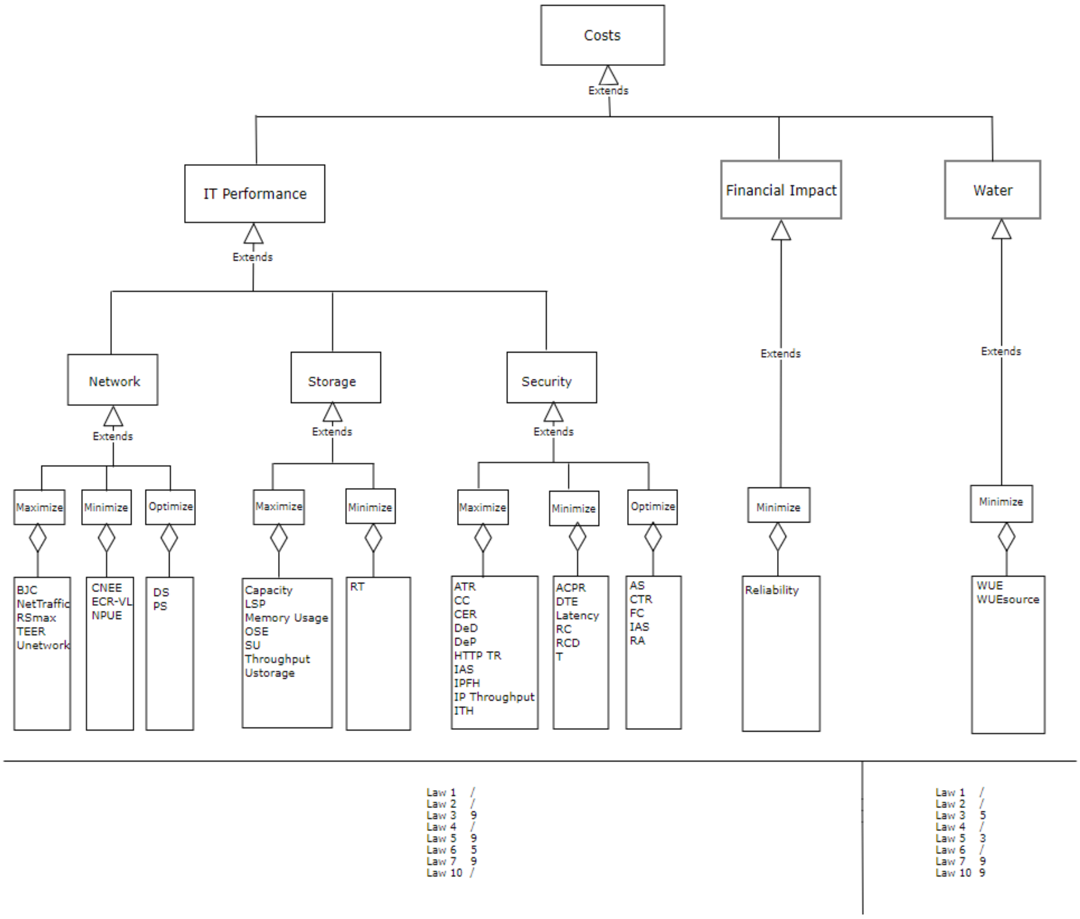


**Figure 19. Costs UML**

While analyzing the sustainability of data centers we also assess the negative impacts of the metrics on the environment in this case, the costs of the data center. The cost UML in figure 19 shows the costs categories IT Performance, Financial impact and water. Their dependencies and metrics that correspond to each category, and each category's vector.

IT Performance focuses on the data center's network, storage and security efficiency. To effectively provide reliable performance of services, data centers must be able to resolve issues and failures within the shortest time possible and guarantee seamless operations to their customers which means increased resources usage for redundancy, an added cost to the data center. IT performance in figure 20 has a vector of {/ / 9 / 9 5 9 /} with Law 1, Law 2, Law 4 and Law 10 (/) having no impact. Law 3 (9) has a strong impact because to achieve efficiency of the network, storage and security components the data center requires more energy for performance which increases the data center's cost of operation. Law 5 (9) is because to ensure reliability when some devices fail, more equipment must be purchased for redundancy in performance.  Law 6&8 (5) because when more resources are used either energy or to produce more IT equipment then there will be some emissions to the environment.  Law 7 (9) has a strong impact because more resources are required to guarantee reliability making the data center operations costlier.

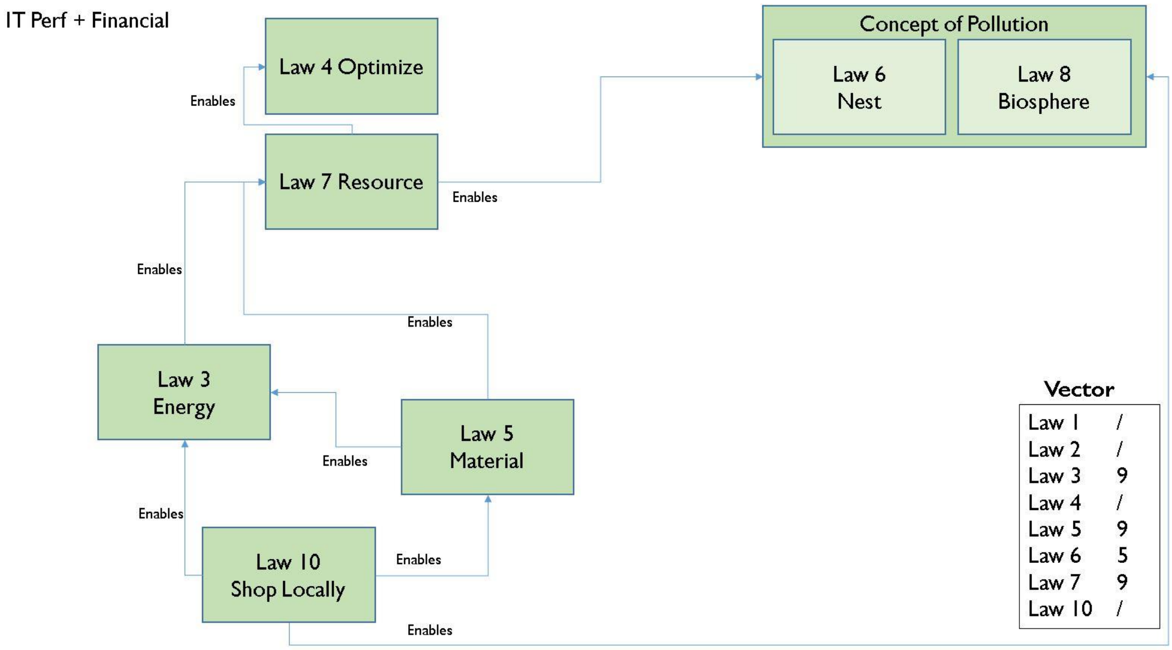


**Figure 20. IT Performance and Financial Nature Relation**

Water as shown in figure 21 has a vector of {/ / 5 / 3 / 9 9} with Law 1, Law 2, Law 4 and Law 6&8 (/) having no impact. Law 3 (5) because reduced water use increases energy use in the data center. Despite the trade-off when it comes to water usage, reduced water usage results to increased electricity use which then translates to increased water use during energy production. Law 5 (3) has minimal impact on water. Law 7 (9) has a strong impact because reduced water use increases resource use such as energy for cooling and other operations in the data center. Law 10 (9) is because water is a resource locally available and is precious therefore should be minimally utilized

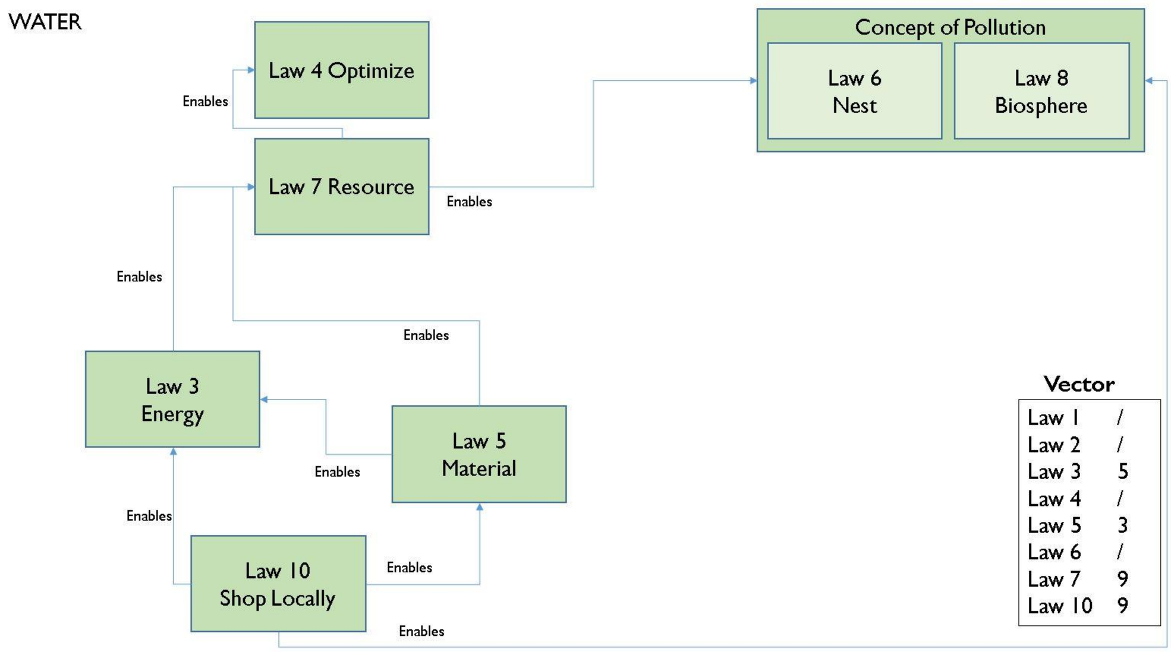


**Figure 21. Water Relation**

# 4 DATA CENTER COMPARISON FRAMEWORK USING AHP

Analytic Hierarchy Process (AHP) introduced by Saaty [6], structures a goal, diversified with criteria and alternatives through pairwise comparisons while relying on expertise judgement for weights and performs consistency checks to ensure the results are not biased which makes decision-making of complex challenges very simple to evaluate. AHP provides a measurement scale that highlight the importance of an alternative or criteria depending on expertise.

AHP decision making follows the listed steps:

1. Identification of the problem or desired information to which the research or user is trying to find a solution.
2. This is followed by objectives grouping of the hierarchy with the goal at the top level followed by the criteria and sub criteria at the lower levels in a detailed manner.
3. Thereafter, the next step is to formulate the pairwise comparison matrices by comparing elements in the upper level with related elements in the next level in the hierarchy.
4. Finally, the last step is to calculate the overall global priority for each element using the weighted values of the priorities from the comparison matrices

AHP has been used to design and assess data center network designs by examining the cost, path length and reliability of the network topology [34]. The increased use of cloud services for organizational needs creates difficulties for customers to decide whose services to use and why they should consider one provider over the other. Through AHP a framework ranking cloud services Quality of Service provides customers with a means of identifying the appropriate providers using a given performance benchmark [35].

The design and usage of intelligent systems requires the storage and processing of data from different sources regarding the devices state of affairs and its surrounding environment to detect faults, schedule for maintenance, optimize performance and energy consumption. The right data dissemination process determine the relevant information about the product that should be stored in the database [36]. To appropriately identify the right data for different situations, fuzzy AHP has been used to develop a framework that selects information from the database using factors such as user concerns, product environment, and business demands. Expertise opinions are used in the data selection approach, with opinions from different sources aggregated and conflicts managed by assigning weights to determine priorities.

In this study, after identifying our objective following the highlighted AHP steps, we calculated the relative score of each category using the measurement scale where 3 highlights slightly more important, 5 moderately important and 9 strongly important [6].

## 4.1 AHP Structure

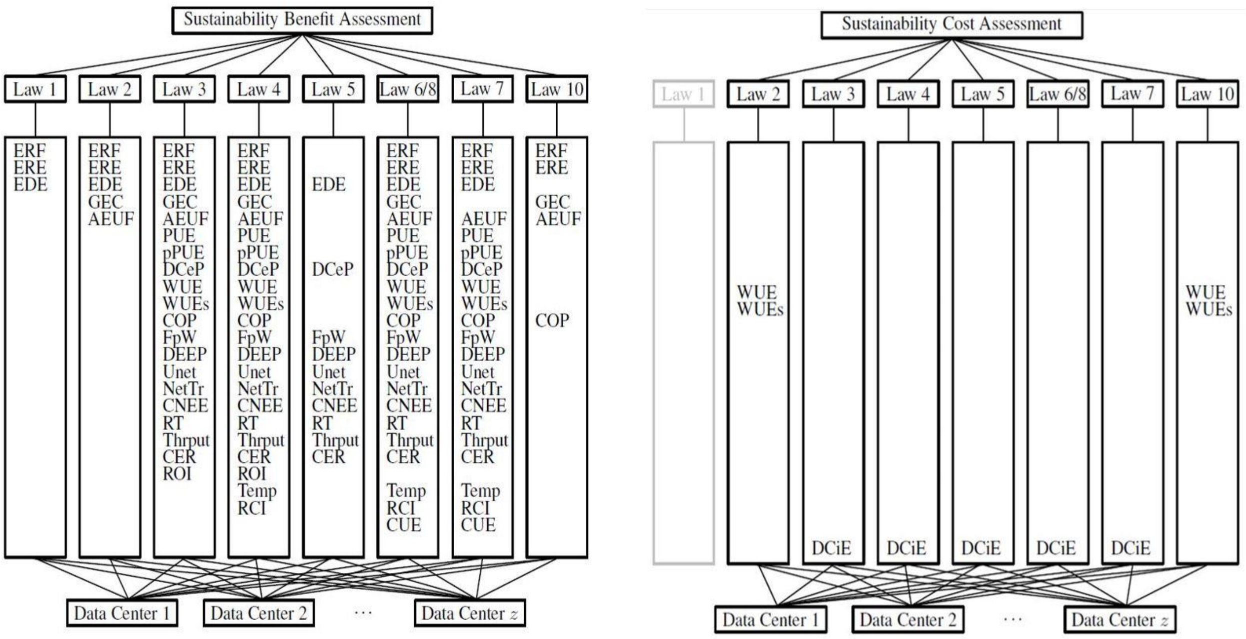


**Figure 22. Benefits Cost Analysis**

The Benefit Cost analysis depicted in the hierarchy in figure 22 represents the metrics that contribute to the positive impacts (benefits) and those that have negative impacts (costs) on the environment. Depending on each metric, the data center leadership and team can easily compute the metrics in each category and determine areas that they can adjust accordingly to minimize harm on the planet while optimizing performance and resource usage. The benefits cost analysis structure is classified into levels with level 0 highlighting the positive and negative impacts. Level 1 shows the nature metrics (Biomimicry Laws) which are used to aggregate the data center ranking. Level 2 lists all the data center metrics in the different dimensions according to their relations with the nature metrics. Thereafter, level 3 shows the alternatives, in this case data centers from which users can make performance comparisons and choose the most appropriate as per the business demands.

## 4.2 Data Center Scenario

In this scenario, we considered data centers from different cities in three countries France [37], Germany [38] and Sweden [39] with the initial parameters extracted from the Cooling Economizer Mode PUE calculator provided by Schneider [40]. The resulting parameters are shown in the table 4. Through the tool we were able to get the PUE and using our data as shown in Appendix 1.

**Table 4. Data Center Parameters**

| Country | France | Germany | Sweden |
|---|---|---|---|
| City | Nice | Karlsruhe | Uppsala |
| Data Center IT Capacity in kW | 1000 | 1000 | 1000 |
| Data Center IT Load | 50% | 50% | 50% |
| IT Operating Environment: Max ◦C | 27 | 27 | 27 |
| No Power & Lighting Considered | / | / | / |

The metric calculations relied on Energy technology and distribution of each country, Energy Water Intensity Factor (EWIF) which shows the amount of water used in each technology to produce electricity [8], and the global emission factor of each energy technology as shown in the appendix, which helped determine the initial total energy consumption, IT equipment energy and carbon emission as per the parameters provided in table 5 which impacts on the metrics values as shown in table 6. The preliminary evaluation focused on ERF, ERE, GEC, PUE, WUE, WUE(source), CUE and DCiE metrics.

**Table 5. Data Center Energy and Emissions**

| | France | Germany | Sweden |
|---|---|---|---|
| | Nice | Karlsruhe | Uppsala |
| **Total Energy Consumption** | | | |
| TC : Total energy consumed per year in KW | 7850000 | 7784360 | 7729312 |
| CW : Total energy consumed per year in KW | 6425724 | 6316027 | 6242066 |
| AC : Total energy consumed per year in KW | 4875329 | 4695410 | 4659830 |
| **IT Equipment Energy Consumption** | | | |
| TC : Energy consumed by IT per year in KW | 4385474.86 | 4373235.95 | 4391654.54 |
| CW : Energy consumed by IT per year in KW | 4385474.86 | 4373235.95 | 4391654.54 |
| AC : Energy consumed by IT per year in KW | 4385474.86 | 4373235.95 | 4391654.54 |
| **Total Carbon Emission** | | | |
| TC : Total C02 emission in kg | 483246 | 3941844.217 | 194778.662 |
| CW : Total C02 emission in kg | 395567.5694 | 3198309.752 | 157300.063 |
| AC : Total C02 emission in kg | 300125.2532 | 2377661.716 | 117427.716 |

**Table 6. Data Center Metrics Values**

| | Traditional Cooling | | | Chilled Water Cooling | | | Air Cooling | | |
|---|---|---|---|---|---|---|---|---|---|
| | France | Germany | Sweden | France | Germany | Sweden | France | Germany | Sweden |
| ERF | 0.02 | 0.09 | 0.07 | 0.02 | 0.09 | 0.07 | 0.02 | 0.09 | 0.07 |
| ERE | 1.7542 | 1.6198 | 1.6368 | 1.4406 | 1.3104 | 1.3299 | 1.0878 | 0.9737 | 0.9858 |
| GEC | 0.19 | 0.3 | 0.58 | 0.19 | 0.3 | 0.58 | 0.19 | 0.3 | 0.58 |
| PUE | 1.79 | 1.78 | 1.76 | 1.47 | 1.44 | 1.43 | 1.11 | 1.07 | 1.06 |
| WUE | 0 | 0 | 0 | 0.1368 | 0.1371 | 0.1366 | 0 | 0 | 0 |
| WUEs | 7.4800 | 2.0400 | 27.8800 | 7.5733 | 2.1349 | 27.9761 | 7.4800 | 2.0400 | 27.8800 |
| CUE | 0.1101 | 0.9013 | 0.0443 | 0.0901 | 0.7313 | 0.0358 | 0.0684 | 0.5436 | 0.0267 |
| DCiE | 0.5586 | 0.5617 | 0.5681 | 0.6802 | 0.6944 | 0.6993 | 0.9009 | 0.9345 | 0.9433 |

Data center cooling utilizes a significant percentage of the facility energy, hence we considered the technology used in the data center. Traditional Cooling which is mostly mechanical is energy and resource intensive. Chilled Water cooling presents a trade-off whereby increased water use might result to depletion while reduced usage of water means increased energy use. Air cooling is free and locally available through the humidity of the air has to be considered to avoid damaging IT equipment.

## 4.3 Results and Discussions

**Table 7. Data Center Benefit and Cost**

| | Traditional Cooling | | Chilled Water Cooling | | Air Cooling | |
|---|---|---|---|---|---|---|
| | Benefit | Cost | Benefit | Cost | Benefit | Cost |
| France | 0.6788 | 0.2105 | 0.6795 | 0.2103 | 0.6748 | 0.21 |
| Germany | 0.3091 | 0.0076 | 0.3373 | 0.0275 | 0.3097 | 0.0473 |
| Sweden | 0.3356 | 1 | 0.307 | 0.998 | 0.3381 | 1 |

The table 7 above highlights the benefits and costs results of the three data centers in France, Germany and Sweden taking into consideration the three cooling technologies: Traditional (mechanical) cooling, Chilled water cooling and Air cooling.

In figure 23 below we can deduce that France benefits ranks better followed by Sweden then Germany. On the other hand, Germany leads in costs followed by France then Sweden. This could be attributed to many factors such as energy technology, energy reuse and carbon emissions among other reasons.

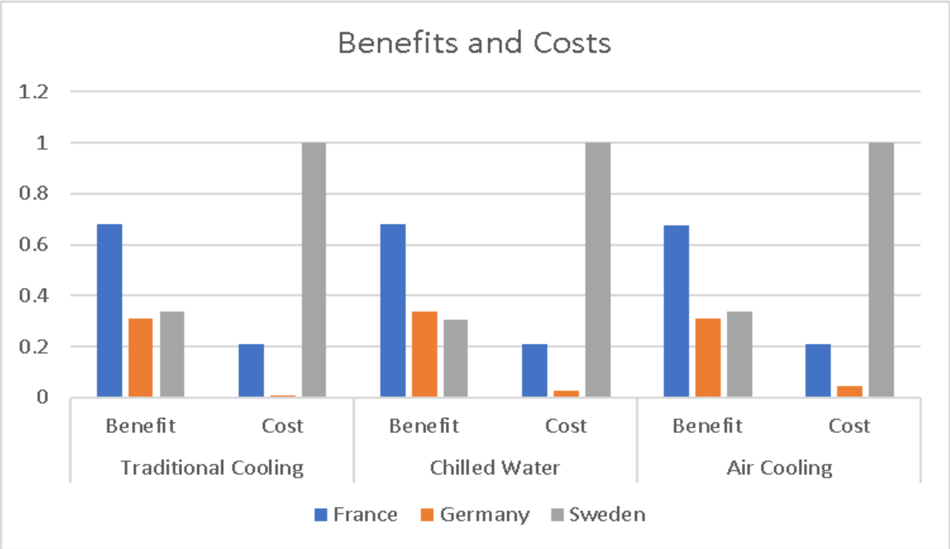


**Figure 23. Data Center Benefit and Cost**

**Table 8. Data Center Benefits/Costs**

| | Benefits/Costs | | |
|---|---|---|---|
| **Data Center** | **Traditional Cooling** | **Chilled Cooling** | **Air Cooling** |
| France | 0.4683 | 0.4692 | 0.4648 |
| Germany | 0.3015 | 0.3098 | 0.2624 |
| Sweden | -0.6644 | -0.691 | -0.6619 |

Table 8 shows the relationship between Benefits/Costs of the three data centers and the figure 24 visualizes the same information which shows France to be performing better followed by Sweden then Germany. This could be as a result of the energy technology used as indicated in the appendix; for instance France electricity distribution has a bigger percentage of 73% Nuclear energy which is clean energy though it has its own limitations. Sweden uses more clean energy specifically 41% hydro though excessive use of water in the USA has been known to cause drought. On the other hand, Germany uses 43% of Coal energy which is from non-renewable sources with high Carbon emissions.

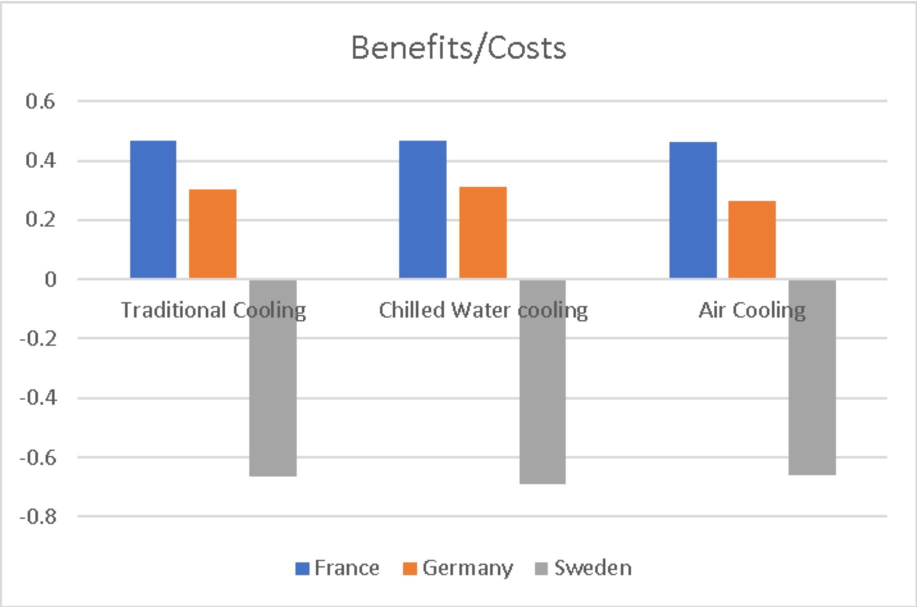


**Figure 24. Benefits/Costs**

### 4.3.1 Traditional Cooling

**Table 9. Traditional Cooling Benefits**

| Traditional Cooling Benefits | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Use waste as a resource | Diversify and cooperate to use the habitat | Gather and use energy efficiently | Optimize rather than maximize | Dont foul the nest | Dont draw down resources | Shop locally |
| FR | 0.9515 | 0.9593 | 0.5129 | 0.5008 | 0.4574 | 0.5304 | 0.9544 |
| GE | 0.0485 | 0.2239 | 0.5689 | 0.4526 | 0.3521 | 0.3151 | 0.147 |
| SW | 0.0916 | 0.0755 | 0.0532 | 0.4209 | 0.5663 | 0.5189 | 0.0856 |

Traditional cooling consumes more energy than the other cooling technologies. Table 9 above and figure 25 below represent the three data center's ranking in terms of the nature metrics (Biomimicry Laws). France ranks better in terms of the laws benefits followed by Sweden then Germany in third place.

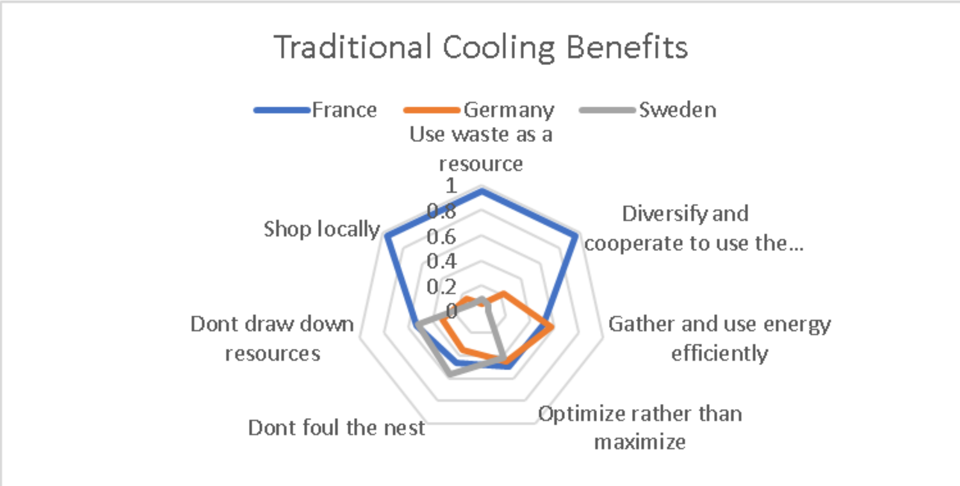


**Figure 25. Traditional Cooling Benefits**

**Table 10. Traditional Costs**

| Traditional Cooling Costs | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Use waste as a resource | Diversify and cooperate to use the habitat | Gather and use energy efficiently | Optimize rather than maximize | Dont foul the nest | Dont draw down resources | Shop locally |
| FR | 0 | 0.2105 | 0 | 0 | 0 | 0 | 0.2105 |
| GE | 0 | 0 | 0.3296 | 0.3296 | 0.3296 | 0.3296 | 0 |
| SW | 0 | 1 | 1 | 1 | 1 | 1 | 1 |

Table 10 and figure 26 show the traditional costs and Sweden ranks higher in costs (negative impacts) followed by Germany and then France.

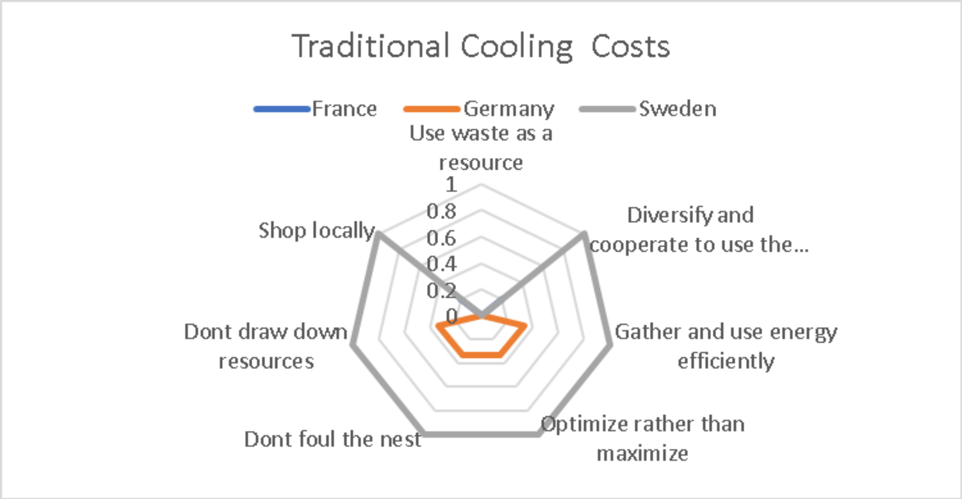


**Figure 26. Traditional Cooling Costs**

**Table 11. Traditional Cooling Benefits/Costs**

| Traditional Cooling Benefits/Costs | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Use waste as a resource | Diversify and cooperate to use the habitat | Gather and use energy efficiently | Optimize rather than maximize | Dont foul the nest | Dont draw down resources | Shop locally |
| FR | 0.9515 | 0.7488 | 0.5129 | 0.5008 | 0.4574 | 0.5304 | 0.7439 |
| GE | 0.0485 | 0.2239 | 0.2393 | 0.123 | 0.0225 | -0.0145 | 0.147 |
| Sw | 0.0916 | -0.9245 | -0.9468 | -0.5791 | -0.4337 | -0.4811 | -0.9144 |

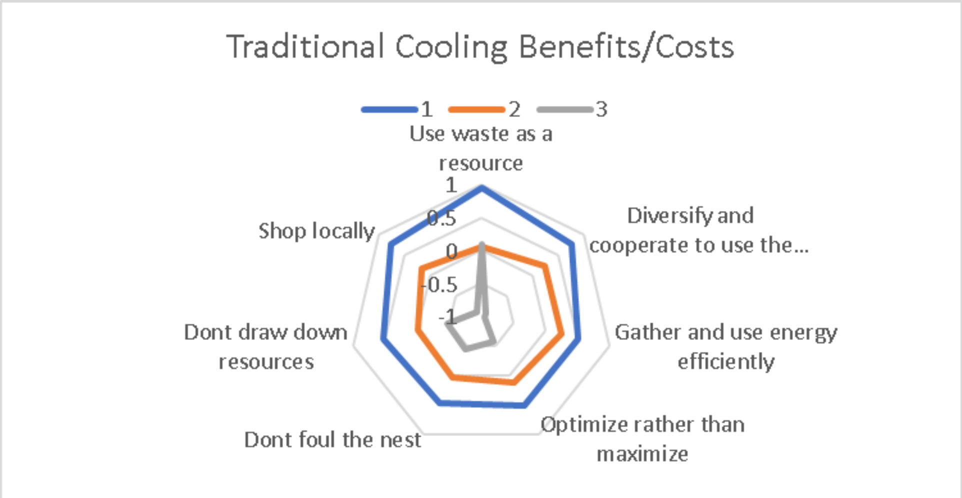


**Figure 27. Traditional Cooling Benefits/Costs**

In table 11 and figure 27 the traditional benefits/costs performance in the nature metrics France ranks first followed by Germany and then Sweden.

### 4.3.2 Chilled Water Cooling

**Table 12. Chilled Water Cooling Benefits**

| Chilled Water Cooling Benefits | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Use waste as a resource | Diversify and cooperate to use the habitat | Gather and use energy efficiently | Optimize rather than maximize | Dont foul the nest | Dont draw down resources | Shop locally |
| 1 | 0.9429 | 0.952 | 0.5185 | 0.5028 | 0.4564 | 0.5296 | 0.9463 |
| 2 | 0.0571 | 0.2249 | 0.566 | 0.4492 | 0.3487 | 0.3121 | 0.1491 |
| 3 | 0.0946 | 0.078 | 0.0559 | 0.4237 | 0.5691 | 0.5212 | 0.0884 |

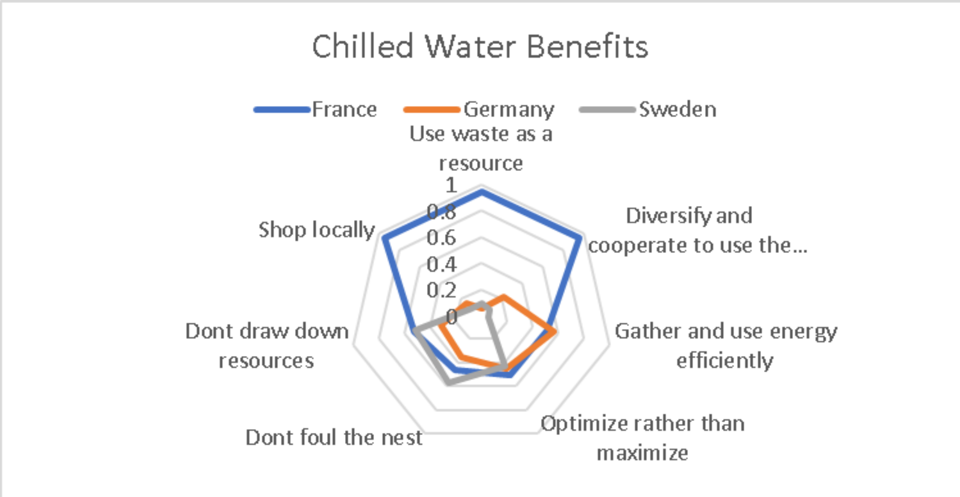


**Figure 28. Chilled Water Cooling Benefits**

Table 12 and figure 28 above highlight the benefits of cooling data centers using chilled water and here even though France ranks better in other nature metrics, Sweden does better in minimal harmful emissions into the environment while Germany has more pollution mainly due to the usage of Coal energy. The challenge is to ensure that water usage is reduced, therefore, data centers have to choose between using more electrical energy with more emissions or more water usage with reduced emissions but a likelihood of depleting water.

**Table 13. Chilled Water Costs**

| Chilled Water Costs | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Use waste as a resource | Diversify and cooperate to use the habitat | Gather and use energy efficiently | Optimize rather than maximize | Dont foul the nest | Dont draw down resources | Shop locally |
| FR | 0 | 0.2105 | 0 | 0 | 0 | 0 | 0.2105 |
| GE | 0 | 0.002 | 0.7448 | 0.7448 | 0.7448 | 0.7448 | 0.002 |
| SW | 0 | 0.998 | 1 | 1 | 1 | 1 | 0.998 |

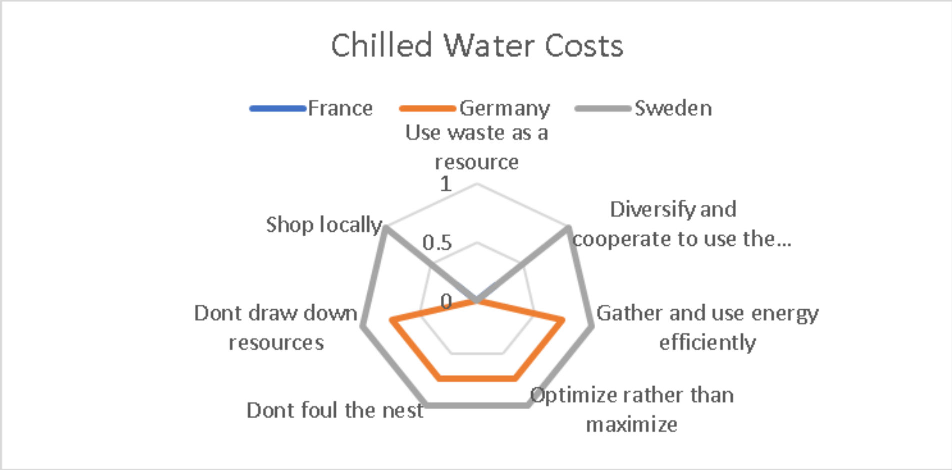


**Figure 29. Chilled Water Costs**

Table 13 and figure 29 show the costs associated with chilled water usage which are negative impacts and here, Sweden ranks higher since it uses water that is locally available followed by Germany.

**Table 14. Chilled Water Benefits/Costs**

| Chilled Water Benefits/Costs | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Use waste as a resource | Diversify and cooperate to use the habitat | Gather and use energy efficiently | Optimize rather than maximize | Dont foul the nest | Dont draw down resources | Shop locally |
| FR | 0.9429 | 0.7415 | 0.5185 | 0.5028 | 0.4564 | 0.5296 | 0.7358 |
| GE | 0.0571 | 0.2229 | -0.1788 | -0.2956 | -0.3961 | -0.4327 | 0.1471 |
| SW | 0.0946 | -0.92 | -0.9441 | -0.5763 | -0.4309 | -0.4788 | -0.9096 |

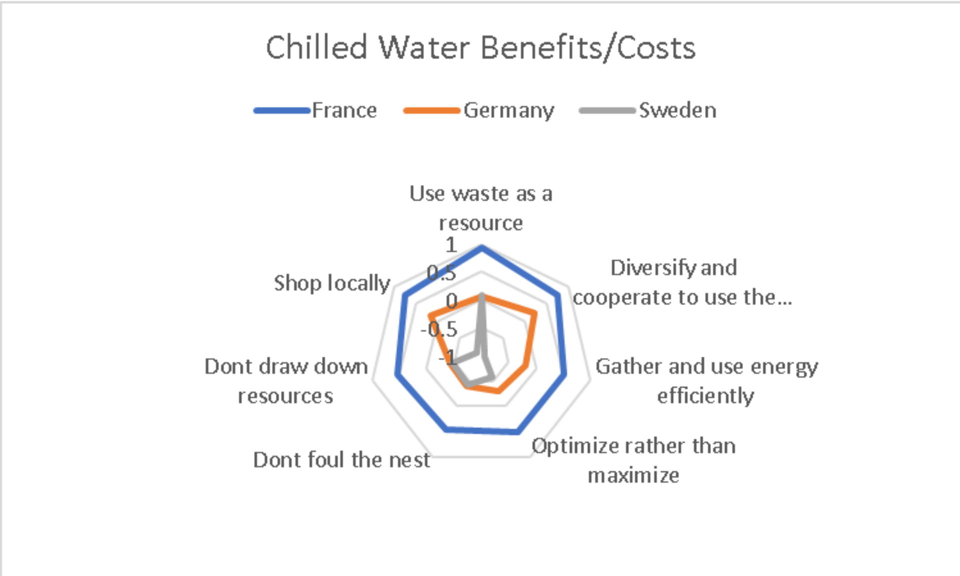


**Figure 30. Chilled Water Benefits/Costs**

Analyzing the information in table 14 and figure 30 which is chilled water benefits/costs we can see that France performs better followed by Germany then Sweden.

### 4.3.3 Air Cooling

**Table 15. Air Cooling Benefits**

| Air Cooling Benefits | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Use waste as a resource | Diversify and cooperate to use the habitat | Gather and use energy efficiently | Optimize rather than maximize | Dont foul the nest | Dont draw down resources | Shop locally |
| FR | 0.9341 | 0.9445 | 0.5125 | 0.4972 | 0.4507 | 0.5244 | 0.938 |
| GE | 0.0659 | 0.2261 | 0.5691 | 0.4516 | 0.3507 | 0.3145 | 0.1517 |
| SW | 0.1005 | 0.0829 | 0.0604 | 0.4231 | 0.5683 | 0.5211 | 0.0939 |

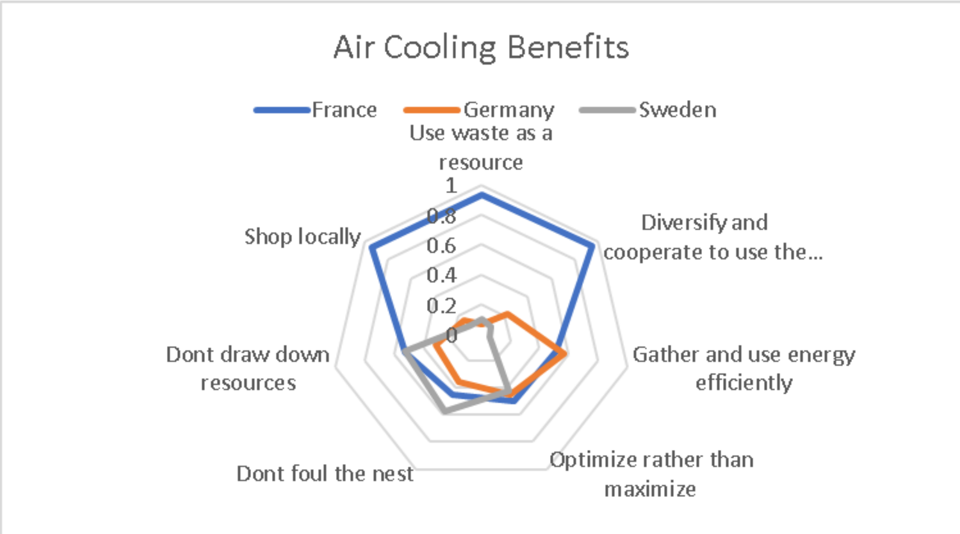


**Figure 31. Air Cooling Benefits**

Air cooling relies on the available free air to keep the IT equipment in optimal operations. Despite the availability of free air, care must be exercise especially in humid areas to avoid reduced reliability of equipment. The table 15 and figure 31 above, France ranks better in the laws followed by Sweden and Germany.

**Table 16. Air Cooling Costs**

| Air Cooling Costs | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Use waste as a resource | Diversify and cooperate to use the habitat | Gather and use energy efficiently | Optimize rather than maximize | Dont foul the nest | Dont draw down resources | Shop locally |
| FR | 0 | 0.2105 | 0 | 0 | 0 | 0 | 0.2105 |
| GE | 0 | 0 | 0.7925 | 0.7925 | 0.7925 | 0.7925 | 0 |
| SW | 0 | 1 | 1 | 1 | 1 | 1 | 1 |

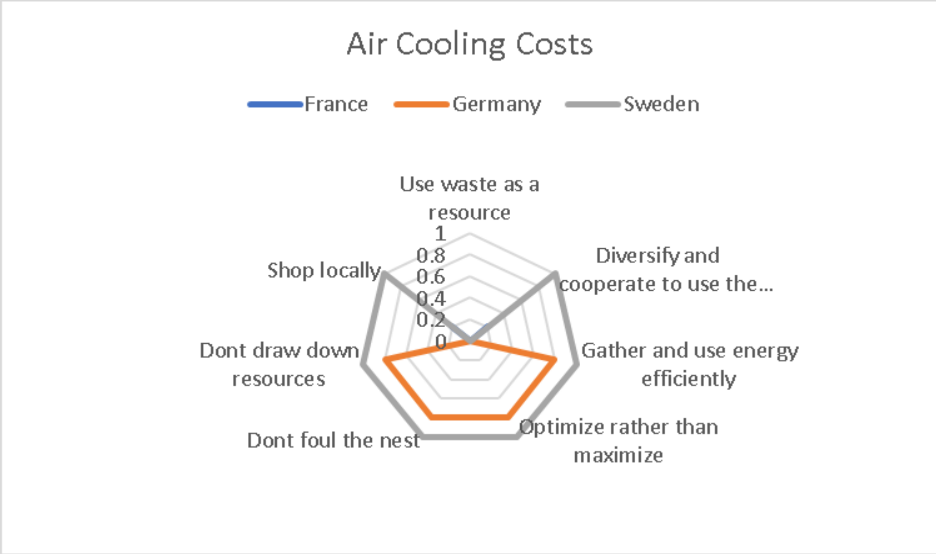


**Figure 32. Air Cooling Costs**

Table 16 and figure 32 shows the costs and Sweden ranks higher followed by Germany

**Table 17. Air Cooling Benefits/Costs**

| Air Cooling Benefits/Costs | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Use waste as a resource | Diversify and cooperate to use the habitat | Gather and use energy efficiently | Optimize rather than maximize | Dont foul the nest | Dont draw down resources | Shop locally |
| FR | 0.9341 | 0.734 | 0.5125 | 0.4972 | 0.4507 | 0.5244 | 0.7275 |
| GE | 0.0659 | 0.2261 | -0.2234 | -0.3409 | -0.4418 | -0.478 | 0.1517 |
| SW | 0.1005 | -0.9171 | -0.9396 | -0.5769 | -0.4317 | -0.4789 | -0.9061 |

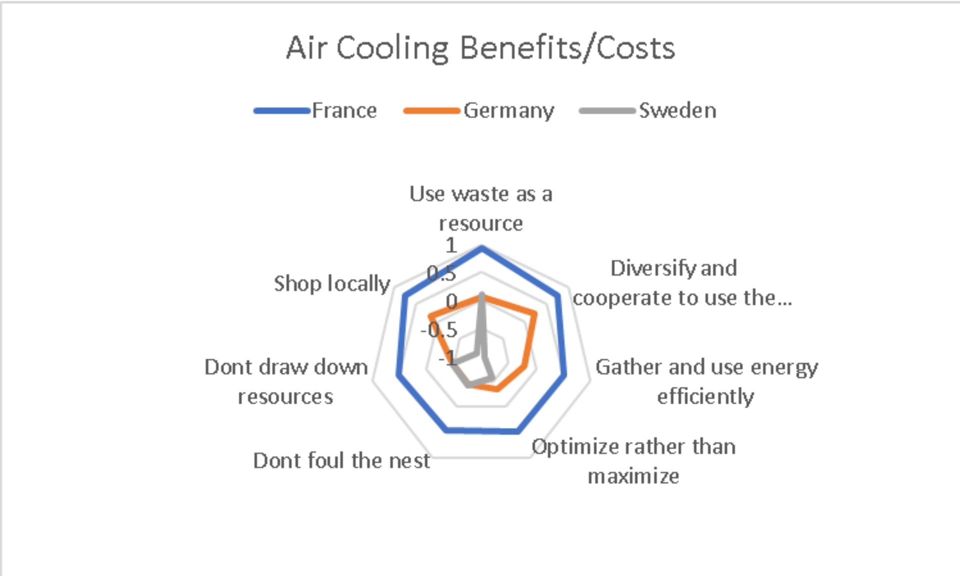


**Figure 33. Air Cooling Benefits/Costs**

In table 17 and 33 air cooling Benefits/Costs, France ranks higher followed by Germany and Sweden

## 4.4 Sustainability

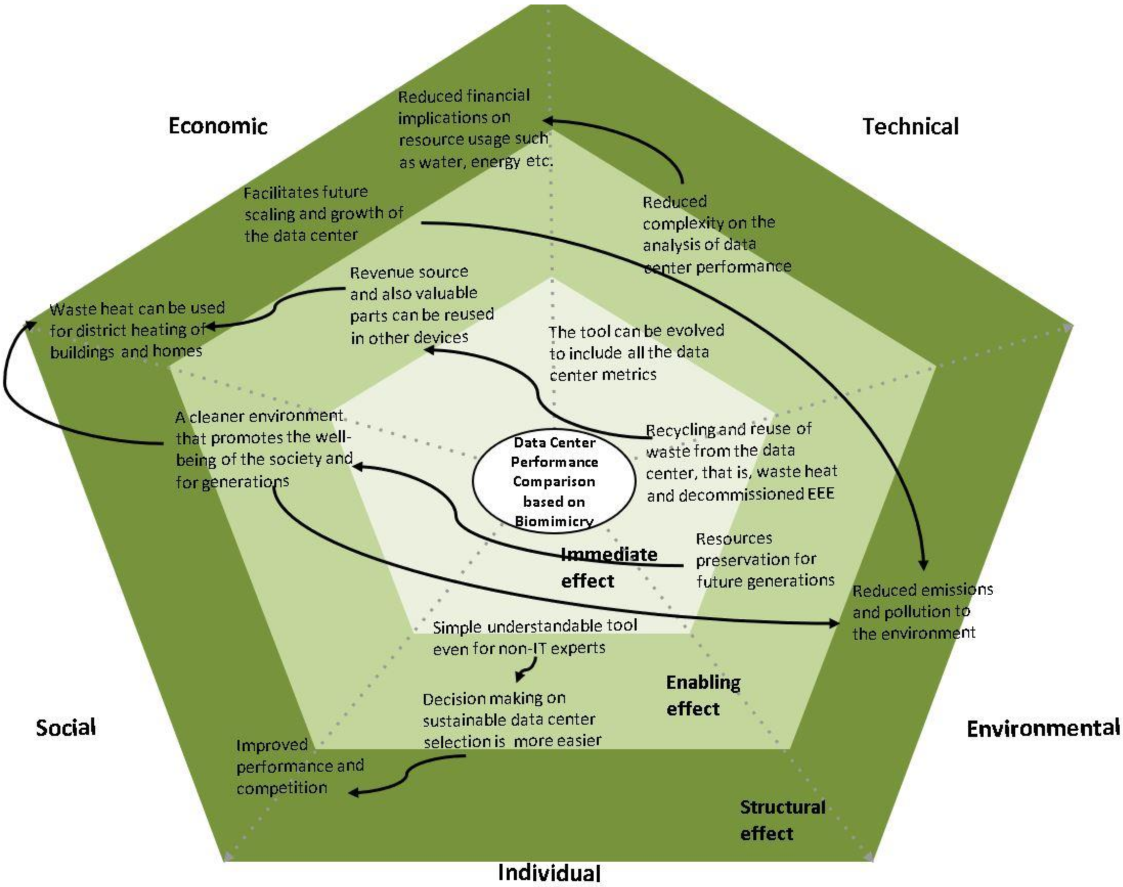


**Figure 34. Sustainability Overview**

Data centers and It organizations need to have a clear picture of their sustainability performance due to the increased energy consumption, Carbon emissions and resource utilization. This is to be able to make informed decisions on areas within the data center that need improvements as well as plan for future growth of new facilities.

Through evaluating data centers performance using the available data center metrics, decision makers can easily plan for increase service provisioning, realize energy costs saving and reduce their operational and environmental costs while providing quality services and also stay in business longer by being able to plan and meet their future needs.

Sustainability can be classified into the following:

- Individual,
- Economical,
- Social,
- Environmental and
- Technical sustainability

For instance in figure 34; individual sustainability, having a simple understandable tool provides decision makers who have expertise in different field with smarter decision making. In environmental sustainability, having a global overview of  areas that need improvement to reduce the impact of data center's operations on the environment. Technically the tool provides a simpler way of analyzing performance for all experts in different functions in the data center. In economic sustainability, data centers can be able to minimize their operational costs and resource usage which enables them to plan accordingly for future growth and expansion. Lastly, a better performing data center provides a conducive space for improved well-being of the people living nearby and with the write cooperation, waste heat can be supplied to nearby buildings and homes.

# 5 CONCLUSION

Data center performance comparisons provide visualization that facilitates optimization of performance through reduced energy consumption, minimal resource usage and reduce emissions into the environment. Users of data center services and data center leadership are better able to make decisions concerning their businesses by having a clear performance indicators that support their operations. There exist frameworks for data center performance assessment that focus on different dimensions leaving out some focus areas which inhibits a holistic view of performance.

Data centers metrics which can be categorized into energy efficiency, material, cooling, carbon, green, recycling, IT performance and financial impacts cover the entirety of data center components and operations. These categories sum up the over 130 data center metrics that exist [3], which is a hard task for experts to concretely measure performance using all the metrics. To streamline the numerous data center metrics we use nature metrics (10 laws of biomimicry) which can be easily understood by experts and non-experts alike. This approach simplifies decision-making processes and makes measurements of performance less tedious.

The presentation of data center's performance using Biomimicry uses Nature's simple principles of thriving on earth and being more eco-friendly as a mature ecosystem [4]. As more data centers are established to meet new demands; designers and investors must vividly make informed decisions in identifying ideal locations, designs and proper planning to sustainably support the growth and expansion. This is because without a proper plan, monitoring and control of ICT systems, earth resources depletion, greenhouse gases emissions will be inevitable. In addition, an evaluation of the benefit cost performance provide important information on areas that can be optimized for continuous improvement which is necessary when making important decisions regarding data centers expansion and scalability.

This proposed performance comparison reduces the complexity and contradictions brought about by data center metrics which when combined with a cost benefit analysis using AHP simplifies the complex decision-making process of individual metrics analysis by ensuring inclusion of all data center crucial components in the evaluation. The comparison appraisal of data centers determines which ones provides better performance in terms of energy efficiency, resource utilization, recycling and environmental awareness which users and businesses can utilize to ensure reliability and improved service provision.

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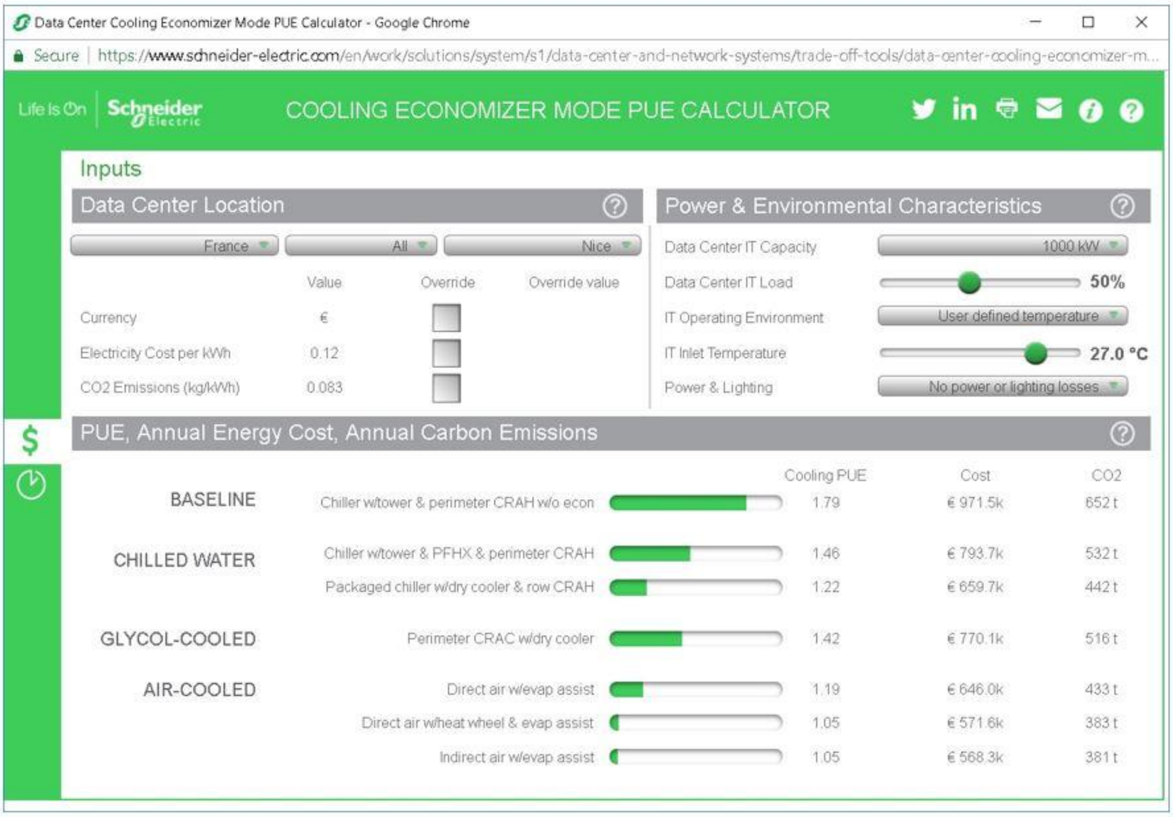
# APPENDIX 1. Experiments Supporting Literature

Cooling Economizer PUE Mode Calculator




The data below was used in the case study analysis. It includes the total data center energy, total energy consumed by IT equipment and amount of Carbon emissions. The electricity distribution in each country, the Carbon factor for each energy technology and EWIF used in energy production.

| | **France** | **Germany** | **Sweden** |
|---|---:|---:|---:|
| | Nice | Karlsruhe | Uppsala |
| TC : Total energy consumed per year in KW | 7850000 | 7784360 | 7729312 |
| CW : Total energy consumed per year in KW | 6425724 | 6316027 | 6242066 |
| AC : Total energy consumed per year in KW | 4875329 | 4695410 | 4659830 |

| | | | |
|---|---:|---:|---:|
| TC : Energy consumed by IT per year in KW | 4385474.86 | 4373235.955 | 4391654.545 |
| CW : Energy consumed by IT per year in KW | 4385474.86 | 4373235.955 | 4391654.545 |
| AC : Energy consumed by IT per year in KW | 4385474.86 | 4373235.955 | 4391654.545 |

| | | | |
|---|---:|---:|---:|
| TC : Total C02 emission in kg | 483246 | 3941844.217 | 194778.6624 |
| CW : Total C02 emission in kg | 395567.5694 | 3198309.752 | 157300.0632 |
| AC : Total C02 emission in kg | 300125.2532 | 2377661.716 | 117427.716 |

| % to produce electricity in countries | France | Germany | Sweden |
|---|---|---|---|
| Hydro | 11% | 3% | 41% |
| Wind | 4% | 12% | 10% |
| Biomass/Biogas | 2% | 9% | 7% |
| Solar (CSP) | 2% | 6% | 0% |
| Geothermal | 0% | 0% | 0% |
| Solar (PV) | / | / | / |
| Nuclear | 73% | 13% | 40% |
| Natural Gas | 6% | 13% | 1% |
| Oil | 0% | 1% | 0% |
| Coal | 2% | 43% | 1% |

| | |
|---|---|
| If Chilled Water : Water used in L in 1 year | 600000 |
| If not Chilled Water : Neglectable | 0 |

| Water used for energy production | EWIF (L/Kwh) |
|---|---|
| Hydro for cooling | 0 |
| Hydro for producing electricity | 68 |
| Wind | 0 |
| Biomass/Biogas | 1.8 |
| Solar (CSP) | 3.3 |
| Geothermal | 1.8 |
| Solar (PV) | 1.8 |
| Nuclear | 3.3 |
| Natural Gas | 0.8 |
| Oil | 1.8 |
| Coal | 2.2 |

| Carbon Emissions | |
|---|---|
| Energy Technology | C02 eq (kg/kWh) |
| Hydro | 0.004 |
| Wind | 0.012 |
| Biomass/Biogas | 0.018 |
| Solar (CSP) | 0.022 |
| Geothermal | 0.045 |
| Sola (PV) | 0.046 |
| Nuclear | 0.016 |
| Natural Gas | 0.469 |
| Oil | 0.84 |
| Coal | 1.001 |

Sample of Pairwise comparison matrices

| **Law 3: Gather and use energy efficiently** | | | | | | |
|---|---|---|---|---|---|---|
| **Value** | **9** | **9** | **5** | **9** | **9** | **9** |
| **Metrics** | ERF | ERE | GEC | PUE | WUE | WUE(source) |
| ERF | **1** | 1 | 9/5 | 1 | 1 | 1 |
| ERE | 1 | **1** | 9/5 | 1 | 1 | 1 |
| GEC | 5/9 | 5/9 | **1** | 5/9 | 5/9 | 5/9 |
| PUE | 1 | 1 | 9/5 | **1** | 1 | 1 |
| WUE | 1 | 1 | 9/5 | 1 | **1** | 1 |
| WUE(source) | 1 | 1 | 9/5 | 1 | 1 | **1** |

| **Law 4: Optimize rather than maximize** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Value** | **9** | **9** | **9** | **9** | **9** | **9** | **9** |
| **Metrics** | ERF | ERE | GEC | PUE | WUE | WUE (source) | CUE |
| ERF | **1** | 1 | 1 | 1 | 1 | 1 | 1 |
| ERE | 1 | **1** | 1 | 1 | 1 | 1 | 1 |
| GEC | 1 | 1 | **1** | 1 | 1 | 1 | 1 |
| PUE | 1 | 1 | 1 | **1** | 1 | 1 | 1 |
| WUE | 1 | 1 | 1 | 1 | **1** | 1 | 1 |
| WUE (source) | 1 | 1 | 1 | 1 | 1 | **1** | 1 |
| CUE | 1 | 1 | 1 | 1 | 1 | 1 | **1** |

| **Law 2: Diversify and cooperate to fully use the habitat** | | |
|---|---|---|
| **Value** | **5** | **5** |
| **Metrics** | WUE | WUE (source) |
| WUE | **1** | 1 |
| WUE (source) | 1 | **1** |

# The Benefits AHP Code