A Pre-Feasibility Analysis on using Renewable Energy to Power Amazon.com, Inc. Operations

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Declaration

‘This dissertation is my own original work and has not been submitted elsewhere in fulfilment of the requirements of this or any other award’.

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Abstract

Amazon.com, Inc. has pledged to be fully powered by renewable energy by 2025 and this paper aims to assess the feasibility of this commitment. This is done by achieving two objectives: 1. Estimate the total energy demand of Amazon's operation and 2. Determine the capacity of a renewable energy project required to meet this demand. Secondary data on energy consumption obtained from peer-reviewed literature, government publications and reputable industry consultants was used to estimate the energy demand of Amazon's key operations: e-commerce, Amazon Web Services (AWS), Whole Foods Market grocery chain, offices and last-mile delivery service with electric vans. The total energy demand estimated was 41.4 TWh per year. A renewable energy project testing software, RETScreen 4, was used to determine the size of a solar photovoltaic (PV) project and an onshore wind project that could meet Amazon's estimated total energy demand. The results showed that a solar PV project of 16 GW capacity or an onshore wind project of 18.3 GW capacity could produce enough electricity annually to fulfil the energy demand estimated. Based on cost and land area considerations for the renewable energy projects, this paper concludes that it is highly feasible for Amazon to achieve their renewable energy commitment. Further research using primary data on Amazon's total energy consumption and renewable project site-specific parameters would improve the accuracy of this feasibility analysis.

Acknowledgements or Dedication

I am most thankful for the following people:

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Chapter 1: Introduction

Companies and non-government institutions are increasingly making commitments to reduce their contributions to anthropogenic climate change. Initiatives like RE100 have seen companies pledging to run their operations on 100 percent renewable energy by a target deadline. Despite public commitments to doing better, there remains a huge variability in level of disclosure about the companies' strategy to achieve such goals. One such company is Amazon.com, Inc. who has been leading efforts to decarbonise their operation with their Climate Pledge initiative that commits to achieving carbon net-zero by 2040. A key part of achieving their goal is to reduce their carbon footprint by powering operations with 100 percent renewable energy by 2025. However, there is a lack of publicly available information regarding their strategy which makes independent analysis of its feasibility, especially due to the size of their operations, very challenging. Research in this area would contribute to the existing body of knowledge about the energy transition in corporations and encourage decarbonisation efforts among businesses. This paper aims to analyse the feasibility of Amazon's commitment to using 100 percent renewable energy by achieving two objectives:

1. Estimate the energy demand of Amazon's key operations and
2. Determine the size of a potential solar photovoltaic (PV) farm or onshore wind farm that could power the operations.

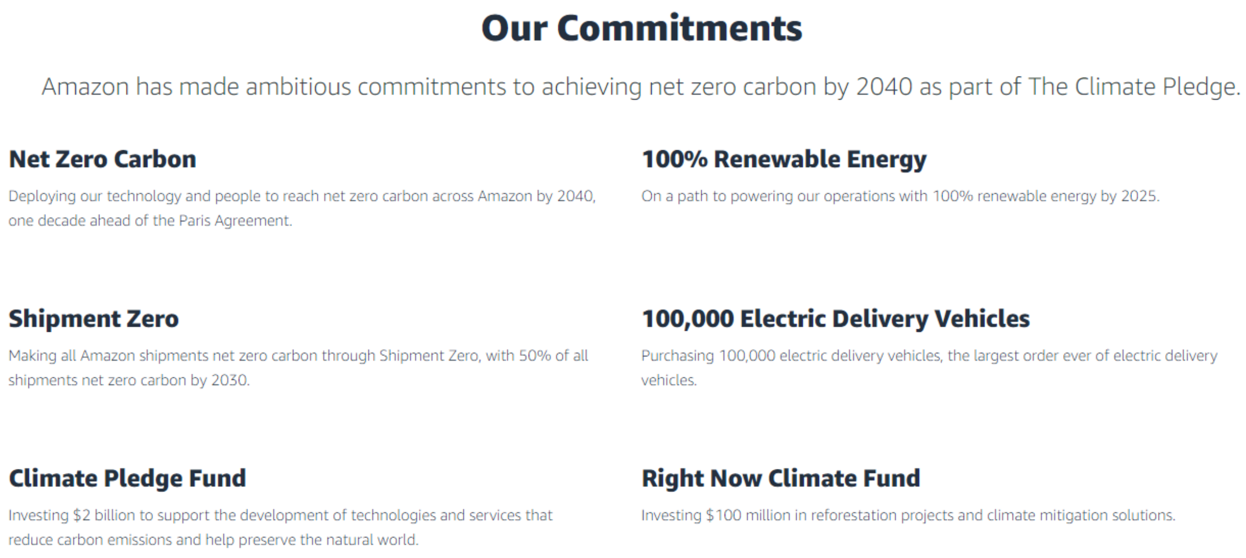
The energy demand from Amazon's key operations will be estimated with a bottom-up approach where possible, using energy consumption data collected from peer-reviewed literature, official reports, and industry consultancy publications. Due to lack of publicly available data, a top-down approach will be used for Amazon's cloud data centre operations. A renewable energy project testing software, RETScreen 4, would be used to size a solar photovoltaic (PV) project and an onshore wind project that would be capable of meeting the total energy demand estimated.

The paper is structured as follows: Background provides some background context on Amazon the company and their major operations that are considered in this study. Literature Review is an overview of the most relevant literature on energy use in the respective industries of Amazon's operations. Methodology specifies the formulas used to determine the total estimated energy demand and the parameters selected for RETScreen projects testing. Analysis details the calculation and results of estimated energy demand in each operation, and the results from the two RETScreen projects. Finally, Discussion and Conclusions assesses the feasibility of Amazon's renewable energy commitment based on the results obtained in the previous section and proposes recommendations for future research.

Chapter 2: Background

Amazon's Climate Pledge

Figure 1: Amazon's Climate Pledge Commitments



Our Commitments

Amazon has made ambitious commitments to achieving net zero carbon by 2040 as part of The Climate Pledge.

Net Zero Carbon

Deploying our technology and people to reach net zero carbon across Amazon by 2040, one decade ahead of the Paris Agreement.

100% Renewable Energy

On a path to powering our operations with 100% renewable energy by 2025.

Shipment Zero

Making all Amazon shipments net zero carbon through Shipment Zero, with 50% of all shipments net zero carbon by 2030.

100,000 Electric Delivery Vehicles

Purchasing 100,000 electric delivery vehicles, the largest order ever of electric delivery vehicles.

Climate Pledge Fund

Investing $2 billion to support the development of technologies and services that reduce carbon emissions and help preserve the natural world.

Right Now Climate Fund

Investing $100 million in reforestation projects and climate mitigation solutions.

(The Climate Pledge, n.d.)

Amazon has committed to a carbon net-zero target by 2040 and plans to power their operations with 100% renewable energy by 2025 as shown in Figure 1. They claim to have reached 42% renewable energy across their business in 2019 and is on track to meet their 2025 goal. (Renewable Energy, n.d.) As of April 2021, Amazon has a renewable energy portfolio capacity of 8.5 GW consisting of 206 solar and wind projects. (Renewable Energy, n.d.)

Key Operations

E-commerce Platform and Logistical Fulfilment Service

Amazon is the largest e-commerce firm in the world and online sales makes up the bulk of Amazon's revenues, amount to $197 billion in 2020. (Amazon.com, Inc., 2021) A significant portion of sales on Amazon websites are made up by third-party sellers, which generated revenue of $80.5 billion in 2020. (Amazon.com, Inc., 2021) This can be attributed to the logistical services of inventory storage and delivery offered by Amazon to businesses and independent sellers in addition to the e-commerce platform.

Cloud Computing – Amazon Web Services

Amazon Web Services (AWS) is the world's most comprehensive and broadly adopted cloud platform, offering over 200 fully featured services from data centres globally. Millions of customers—including the fastest-growing startups, largest enterprises, and leading government agencies—are using AWS to lower costs, become more agile, and innovate faster. (What is AWS, n.d.) AWS has 80 Availability Zones (AZ) within 25 geographic Regions, where each AZ is one or more discrete data centres with redundant power, networking, and connectivity in an AWS Region. (Global Infrastructure Regions & AZs, n.d.) This segment of the company is quickly growing and can be expected to overtake the e-commerce segment as Amazon's main revenue generating operation.

Amazon Physical Stores

In addition to own brand stores like Amazon Fresh, Amazon Pantry, Amazon Bookstore, Amazon bought the Whole Foods Market grocery chain in 2017 and currently operates 503 stores in the US. Physical stores generated $16.2 billion in revenues in 2020. (Amazon.com, Inc., 2021)

Chapter 3: Literature Review

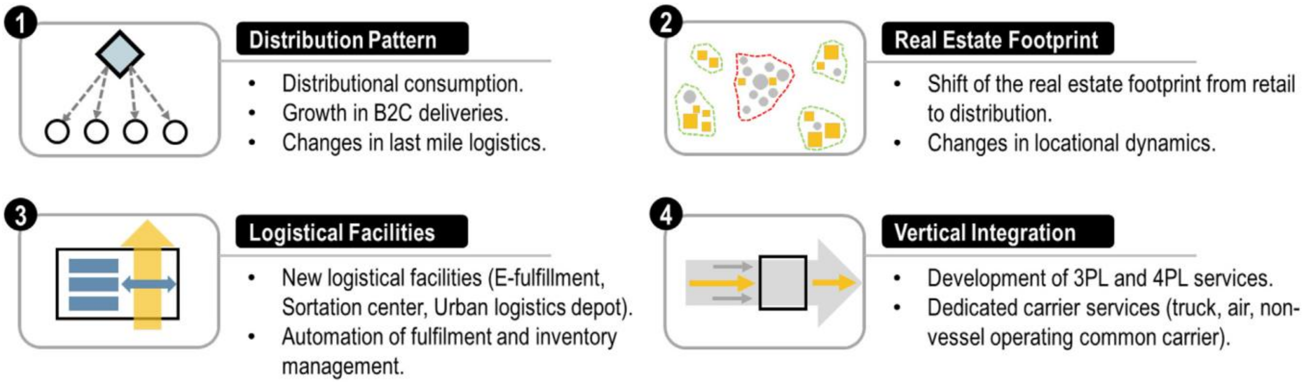
E-commerce & Logistics

E-commerce is defined as the buying and selling of good or services via the internet, or the transmitting of funds or data, over an electronic network, primarily the internet. Since its emergence as a new form of retail in the early 2000s, global e-commerce has grown to a market capitalisation of US$ 4.28 trillion in 2020. (Sabanoglu, 2021) Amazon currently leads the industry as the biggest consumer internet and online services company worldwide and commanded a market capitalisation of US$ 1.597 trillion as of September 2020 or about 37 percent of market share. (Sabanoglu, 2020)

E-Commerce Logistics System

Although several aspects of e-commerce are perceived as virtual retailing, Rodrigue (2020) argues that e-commerce can better be understood from a freight distribution perspective. since it differs from traditional retailing most significantly as the fundamental characteristics are on distribution and delivery. E-commerce has high throughput rates, small heterogenous packages, delivery to home, offices, and are increasingly delivered in very short amount of time (note: Amazon's Same Day or Next delivery) that presents logistical challenges unique to this form of retail. Rodrigue (2020) identifies a general logistical model of e-commerce operations as shown in figure 2, described as a new freight landscape that concerns its demand structure, the modes and terminals used, and crucially, the last-mile that commonly takes place in urban areas. (Rodrigue, Dablanc and Giuliano, 2017)

Figure 2: The E-commerce Freight Landscape

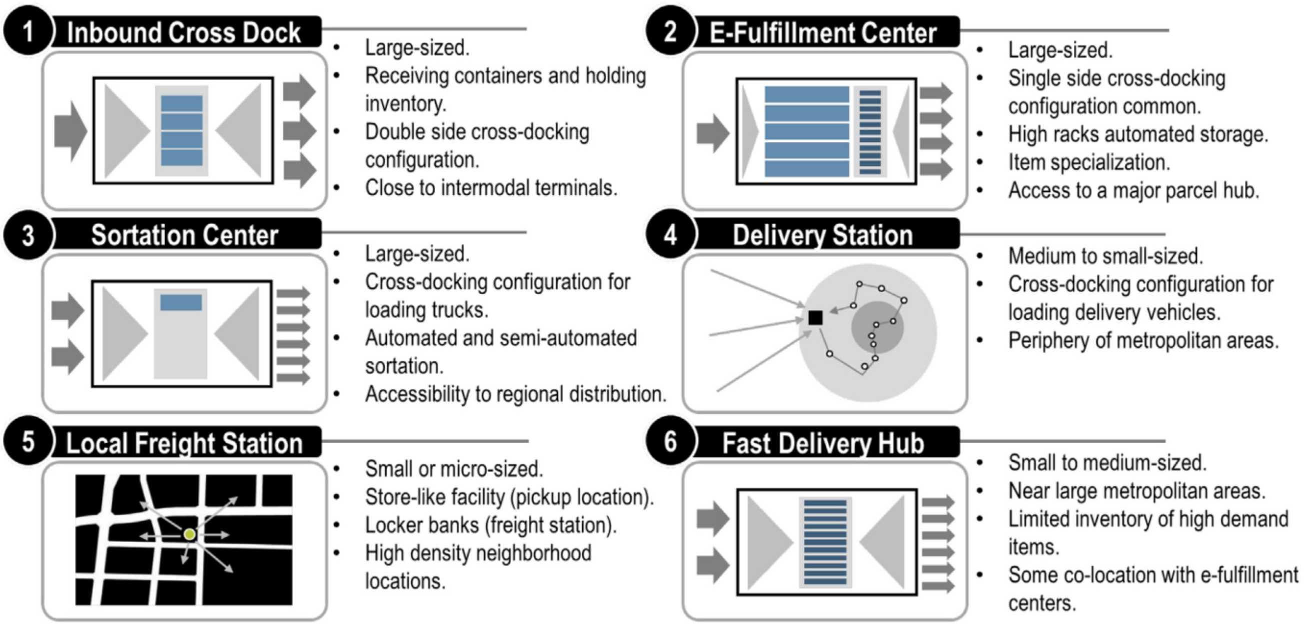


(Rodrigue, 2020)

Logistics Facilities

The focus on logistical efficiency to fulfil short delivery times and high throughput requirements that is differentiates e-commerce from traditional retail has led to the development of entirely new types of distribution facilities.

Figure 3: Logistics Facilities Supporting E-commerce



(Rodrigue, 2020)

Inbound cross-dock (IXD) facilities (1) are primary located near major intermodal terminals such as port and rail yards to receive international imported goods in containers. They function like transloading facilities but service exclusively e-fulfilment centres, where unloading and storing inventories occur until they are demanded and sent to fulfilment centres in trucks. (Rodrigue, 2020)

E-Fulfilment centres (2) are massive facilities with footprint usually between half and one million square feet which houses the assembling operation of individual online orders. Picking operation & automation to fulfil high throughput requirements.

Parcel hubs and sortation centres (3), also massive facilities, then sort out high volumes of parcels bound to an area into smaller batches, preparing them to be sent to the next station which include local post-offices, parcel delivery stations or to subcontracted delivery companies for delivery to customers. Like the e-fulfilment centres, they are located to maximise accessibility to a regional or metropolitan distribution system. (Rodrigue, 2020)

Delivery Stations (4) are usually located in the immediate periphery of a metropolitan area or in the central location and are responsible for further sorting parcels bound for specific local delivery routes by delivery vans and other delivery vehicles. (Rodrigue, 2020)

Due to problems associated with home deliveries such as people being at work or school during delivery hours, resulting in increased cost from parcel returns and redeliveries, alternative solutions for delivery destinations have emerged. Pickup locations and local freight stations (5) are used when deliveries are not made directly to the final address. These facilities are typically small and situated in accessible high-density locations. (Rodrigue, 2020) Options include pick-up-drop-off

(PUDO) points in places like grocery stores, newsagent's, shopping malls, and parcel lockers that require verification upon retrieval. (Orenstein, Raviv and Sadan, 2019)

Fast delivery hubs (6) are located within large metropolitan areas carrying an inventory of high-demand items which are pre-positioned ahead of expected demand to service fast deliveries within a lead time of 48 hours. (Rodrigue, 2020)

Energy Use in Logistics

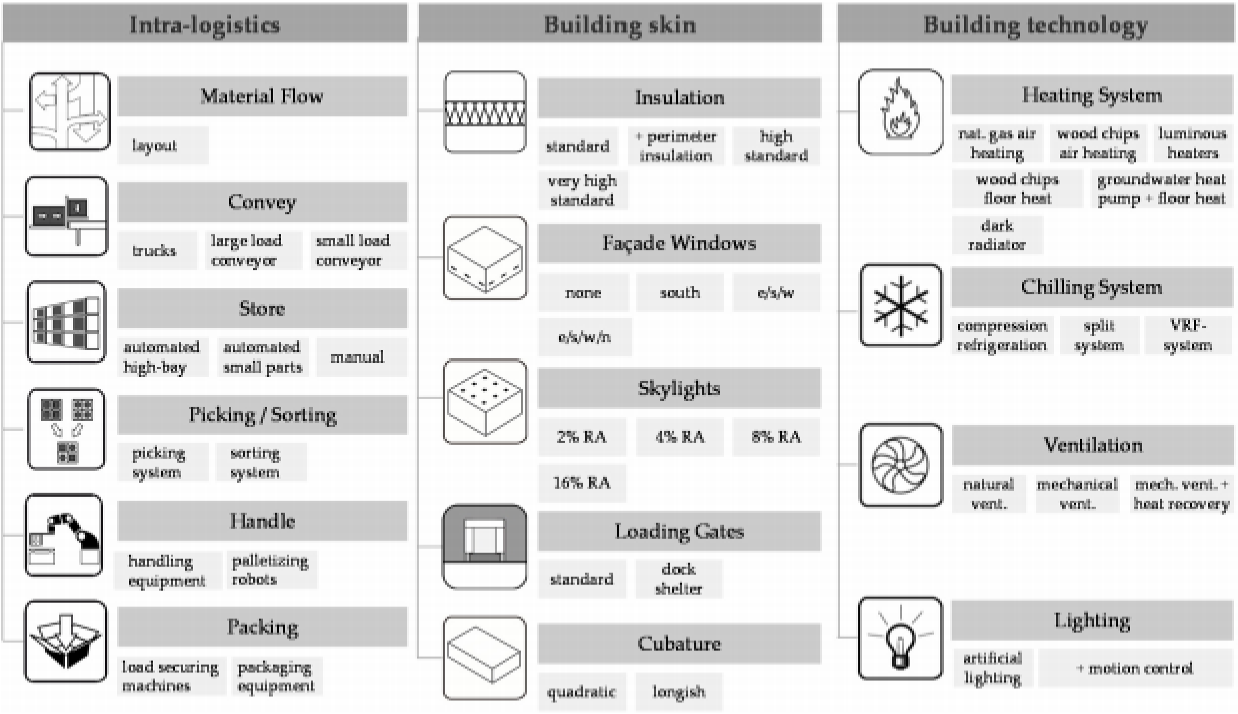
There is a lack of studies on quantifying energy consumption in e-commerce fulfilment centres and other facilities in existing literature, as most are concerned with minimising cost, improving fulfilment performance by increasing efficiency of sorting and picking operations, and more recently, improving the carbon footprint of operations in the facilities. Estimating energy consumption and energy use intensity (EUI) of fulfilment centres is highly complex as fulfilment centres are uniquely designed to serve the requirements of the region they are located in. While studies relating specifically to e-commerce fulfilment centres may be lacking, research conducted on building types with comparable logistical operations such as distribution centres, e-grocery warehouse and warehouses in general are better studied.

Zajac and Kwasniowski (2017) analysed the components of a logistics warehouse systems that contributes to the warehouse energy balance and discusses options to minimise energy consumption in progress towards zero-energy buildings. The study however did not account for intra-logistics operations within the building and therefore heat losses of intra-logistics equipment into account as heat sources. Ries, Grosse and Fichtinger (2016) estimated the energy demand of different logistical warehouses based on 4 types of warehouse technology employed and their corresponding reduction in carbon emission. Energy Use Intensity (EUI) for the respective types of warehouses was lacking as the energy demand estimated was calculated only for the median warehouses in the US. The limited selection of warehouse types also does not include more recent technology which will be discussed in the later next section. Freis, Vohlidka and Günthner (2016) developed a more holistic model to calculate the energy demand of logistics centres based on their intra-logistics design, building technology, and building skin, leading to estimation of carbon emissions by the whole facility. The model requires many technical inputs for estimation of total energy demand which might be difficult to obtain for individual logistics centres. Due to the lack of such information about Amazon's logistical centres, their energy demand in this paper will be estimated using the average energy demand of general logistics warehouses in addition to the estimated energy demand of the intra-logistic system utilised in Amazon's facilities.

According to E Source, a utility consulting firm, nonrefrigerated warehouses in the US use an average of 6.1 kWh/sqft of electricity and 13,400 Btu/sqft of natural gas annually. (Warehouses, 2020) This amounts to the total annual energy consumption of 10.0 kWh/sqft. In comparison, refrigerated warehouses use much more electricity, consuming an average of 24.9 kWh/sqft of electricity and 9,200 Btu/sqft of natural gas per year. (Warehouses, 2020) The total annual energy consumption amounts to 27.6 kWh/sqft. This is quite consistent with findings by U.S. Environmental Protection Agency (EPA) showing that the EUI of distribution centres in the US has a median of 75,000 Btu/sqft (22.0 kWh/sqft) and mode of 50,000 Btu/sqft (14.7 kWh/sqft). (DataTrends: Energy Use in Distribution Centers, 2016)

Freis, Vohlidka and Günthner (2016) identified the base elements of the sub-systems intralogistics in a logistics centre as summarised the Figure 4.

Figure 4: Base Elements of the Sub-systems Intralogistics



(Freis, Vohlidka and Günthner,2016)

Intralogistics Systems

Among the various process involved in intra-logistics, ordering picking has long been identified as the most labour-intensive and costly activity, where underperformance can lead to unsatisfactory service and high-operational cost for the whole supply chain. (de Koster, Le-Duc and Roodbergen, 2007) Order picking is also the most time and energy consuming process in warehouses. As such, there are extensive available literature on this subject to optimise picking operations where service time (Lamballais, Roy and De Koster, 2017; Schleyer and Gue, 2012), distance (Lu, McFarlane, Giannikas and Zhang, 2016), cost (Melacini and Tappia, 2018; Ene and Öztürk, 2011) and energy consumption (Borovinšek, Ekren, Burinskienė and Lerher, 2016; Liu et al., 2021) are used as performance criteria.

Boysen, de Koster and Weidinger (2019) conducted a comprehensive literature review on various warehousing systems used in the e-commerce era. They discussed the forms of warehouse systems that were best suited to the unique requirements of e-commerce warehouse being small orders by customers, large assortment of products, tight delivery schedules of next or even same day deliveries and varying workloads due to volatile demands. Traditional manual picker-to-part system is considered the least productive as pickers spend a large amount of time walking (or driving) to retrieve goods from storage. Their paper examined and detailed the suitability of seven different warehouse system in increasing order of automation: 1. Mixed-shelves storage, 2. Batching, zoning, and sorting, 3. Dynamic order processing, 4. Autonomous Guided Vehicles (AGV) assisted picking, 5. Shelf-moving robots, 7. Advanced picking workstations.

Amazon employs a type of shelf-moving robot in their fulfilment centres, originally named Kiva Systems and renamed to Amazon Robotics after purchase of the company, which is an automated storage and part-to-picker order picking system. The robots work by retrieving a movable shelf rack containing the ordered item, bringing it to a workstation where the picker picks and packs the item, after which the robot moves the shelf rack back into an unused storage area within the designated warehouse floor. (Lamballais, Roy and De Koster, 2017) In 2020, Amazon is estimated to have in excess of 200,000 robots deployed across their global network, where a typical small sortable fulfilment centre has 3,000 robots operating on 3 or 4 floors within the building. (A Supply Chain Consultant Evaluation of Kiva Systems (Amazonrobotics), n.d.)

This system is more commonly referred to as Robotic Mobile Fulfilment System (RFMS), although other terms are also used albeit less frequently. (da Costa Barros and Nascimento, 2021) Lamballais, Roy and De Koster (2017) developed queuing models for RFMS that estimate maximum order throughput, average order cycle time and robot utilisation which is affected by the location of workstations around the storage area. Xu, Yang and Guo (2019) proposed an energy efficiency model for RMFS from analysing the force and work done by the robot during operation and tested using different batch size, storage strategies and workstation locations. They concluded that large batch size, full-turnover storage strategy and storing items with high turn over rates near the workstations produced the greatest energy efficiency. Ghelichi and Kilaru (2021) proposed two analytical models to evaluate the performance of this system, which they referred to as Autonomous Mobile Robots (AMR), in Last-Mile Delivery (LMD) and Meet-In-Aisle (MIA) applications. LMD solution in e-commerce warehouses involve human pickers assigned to zones in the picking area and loading carts of orders which are transported by the robots to the consolidation area. The robots in MIA solutions have greater autonomy and conducts both picking and transporting operation to workstations operated by humans – the system employed in Amazon fulfilment centres. They concluded that the MIA solution performed best under scenarios with large facility and small number of picks per cycle and therefore are most suited for e-commerce warehouse applications whereas LMD solutions perform better in the case of a high pick cycle.

Freight (Transport)

Freight operations in e-commerce businesses are typically served by third-party logistics (3PL) providers. (MWPVL International Inc., 2021) However, Amazon has been increasingly taking control of this aspect of their e-commerce logistics operation, investing in their own airplanes and air terminals (Amazon purchases 11 aircraft from Delta and WestJet to join Amazon Air's network, 2021), expanding their fleet of land freight, and experimenting with novel delivery solutions such as drones (Wilke, 2019) and autonomous robots (Scott, 2019).

The last mile is referred to as the last leg of the delivery process from a regional depot to the recipient (Orenstein et al., 2019) or the final leg of the journey where a product lands in a consumer's hands (Capgemini 2019). It is also the most extensively studied due to inefficient in delivery cost (half truckload on delivery), delivery time per parcel (waiting-load periods at multiple stop) and is impacted by urban traffic congestion. (Özbekler and Karaman Akgül, 2020) Rodrigue, Dablanc and Giuliano (2017) highlighted the complexity of city logistics in four major metropolitan areas and showed substantial variations in the spatial distribution and intensity of urban freight activity between those areas. Kawa (2020) proposed out-of-home delivery as a solution to the last-mile problem where customers are not at home to receive their parcels. Out-of-home solutions include the use of parcel lockers and pick-up-drop-off (PUDO) points to reduce rates of redelivery.

Electric Vehicles

Amazon has announced their plans to deploy 100,000 Rivian electric vans in the US to be used in the last- mile segment of their e-commerce delivery journey. In addition, 1,800 delivery vans were ordered from Mercedes-Benz with plans for deployment in Europe. The available literature on electric freight vehicles is quite extensive even though the application of electric engines in freight operations is quite a recent phenomenon. Interest in this area were attributed to the increasing urgency in decarbonising the transport industry, which is a large contributor of global greenhouse gases that accounted for almost a quarter of global energy-related CO_2 emissions in 2018. (Data & Statistics - IEA, 2018) The development trend of electric vehicles in road passenger and road freight transport was explored in the literature review study by Stopka et al. (2020). Bektaş, Ehmke, Psaraftis and Puchinger (2019) analysed the application of electric vehicles as part of wider study on green freight transportation in the field of Operational Research (OR).

Analysing Potential for Deployment

Feasibility studies were conducted to assess the potential for deploying electric road freight in various locations. Current challenges for deployment of battery electric vehicles include the high cost of batteries, their limited range and long recharge times. (Nicolaides, Cebon and Miles, 2018) This is consistent with results from the case studies by Jahangir Samet, Liimatainen, van Vliet and Pöllänen (2021) which show that the successful trip coverage of battery electric trucks by using available fast-charging facilities was less than 100% in both Finland and Switzerland. In a case study of Rio de Janeiro-Brazil, the use of smaller electric vehicles such as electric tricycles was deemed as the best last-mile delivery option due to both superior cost and greenhouse gas emission performance. (de Mello Bandeira et al., 2019) Other studies considered alternative approaches to overcome the current technological limitations of batteries in electric freight vehicles (EFV) which will be covered in a later section.

Vehicle Optimisation

Some studies developed models to select optimal vehicle design: Wątróbski et al. (2017) developed a multi-criteria analysis of electric vans for urban deliveries; Voytkiv (2020) proposed a methodology for assessing the technical – constructive, energy, functional and economic - efficiency of light-duty electric vehicles; Subramaniam and Dhinakaran (2021) used Solidworks software to model an electric vehicle with single person seating capacity for e-commerce door deliveries.

Operation and Performance on the Road

Research on EFV's performance on the road were evaluated based on energy consumption, cost and greenhouse gas emissions. Yong et al. (2018) assessed the technical performance, economics feasibility and environmental impacts of electric freight vehicles for urban logistics in European cities. Their results showed that energy spent per day or km is strongly related to the gross weight of the vehicle, smaller vehicles (lighter than 3.5 tonnes) are impacted more by temperature changes and need to be charged twice per day as opposed to larger vehicles with full day battery capacity. The total cost of ownership (TCO) is generally favourable for small vehicles, situation dependent for medium vehicles and less favourable for large vehicles due to lower TCO for the conventional option. The study reported an overall reduction of 45% total GHG emissions although it varies greatly in different cities depending on the fuel mix for local electricity production. Fiori and Marzano (2018) proposed a microscopic backward highly-resolved power-based EFVs energy consumption model (EFVs-ECM) that can be used to inform fleet management and planning/policy-making decisions. Olkhova, Roslavtsev and Mykhalenko (2020) reported potential cost savings of at least 41% using electric delivery trucks over diesel trucks for confectionary delivery in Ukraine. External factors that affected performance were identified and quantified based those metrics. Fiori et al., (2019) explored the relationship between traffic conditions and energy consumption of electric vehicles. Using a vehicle simulator: the VT-CPEM (Virginia Tech Comprehensive Power-based Energy consumption model), the found that EVs and EFVs use less energy in the congested traffic scenario than in free-flow traffic scenarios which is opposite to the trend observed for internal-combustion engine vehicles. In assessing the cost-optimal mileage of medium-duty electric vehicles, Taefi, Stütz and Fink (2017) found that a low daily mileage is more cost-efficient at high energy prices or consumption as opposed to using the technical maximum range by intermediate charging and multi-shift usage.

Route Optimisation

Route optimisation was also of great interest due to the limitations of batteries, recharging times and possible lack of adequate charging infrastructure. The pickup and delivery problem for EFV were studied, with Lin and Zhou (2020) investigating the effects of key technological and operating factors on the daily vehicle routing cost of battery electric trucks (BET). They found that economies of scale apply to BET in urban delivery service and found better cost performance in smaller and high customer density service areas. Wang, Wu and Cao (2021) proposed a system to forecast energy consumption and travel time for vehicle routes that includes a genetic algorithm to optimise routing with energy consumption constraints. Soysal, Çimen and Belbağ (2020) approached the problem using a chance-constrained mixed integer non-linear programming model and proposed a linear approximation to estimate energy requirement. Some studies focused on the time window constraints sometimes neglected in route optimisation. Goeke (2019) developed a granular tabu search (GTS) with a policy to determine the amount of energy recharged given time window constraints and demonstrated the partial recharging can be advantageous over full recharging in reducing the number of vehicles and total distance if the planning horizon is short. Raeesi and Zografos (2020) proposed an alternative solution of mobile battery swapping rather than intra-route recharging to overcome the time-constrained vehicle routing problem and developed a methodology and tests to evaluate the efficiency of proposed algorithms.

Charging Behaviour and Infrastructure

Another strategy to overcome the operational limitations of battery electric vehicles is using opportunity charging (OC) where vehicles are charged during operational hours as opposed to conventional charging at home or at work when not in use. This strategy reduces the need for large battery sizes to meet long driving range requirements but is dependent on the availability of charging infrastructure. (Teoh, Kunze, Teo and Wong, 2018) Existing studies on this topic focus on options for opportunity charging solutions and optimising the use of such systems. Londoño and Granada-Echeverri (2019) provides an optimisation model for determining the optimal location strategy of EV charging stations and their routing plan in addition to consideration of impacts on the power grid. Pelletier, Jabali and Laporte (2018) developed a comprehensive mathematical model for depot charge scheduling based on factors such as realistic charging process, time-dependent energy costs and grid restrictions. Nicolaides, Cebon and Miles (2019) estimated that a complete urban charging network for road freight transportation in Cambridge UK would increase power demand by 21.6 MW and energy consumption by 50.6 GWh per year at a cost of £149 million (US$207 million) Teoh, Kunze, Teo and Wong (2018) evaluates the performance of different opportunity charging (OC) strategies (stationary/non-stationary and conductive/inductive) on CO_2 emission and lifecycle costs. They found that using OC for battery electric vehicles reduced CO_2 emissions by up to 39% and generally resulted in lower lifecycle costs without a significant trade-off of the decarbonisation benefits. Deflorio and Castello (2017) presented a model for assessing traffic and energy performance of dynamic charging-while-driving (CWD) road systems for fully electric vehicles. Using an advanced vehicle simulator, ADVISOR, Nicolaides, Cebon and Miles (2018) found that deep decarbonisation of the UK's road freight system by electrification of long haul vehicles would be feasible with the installation of dynamic charging or CoM infrastructure.

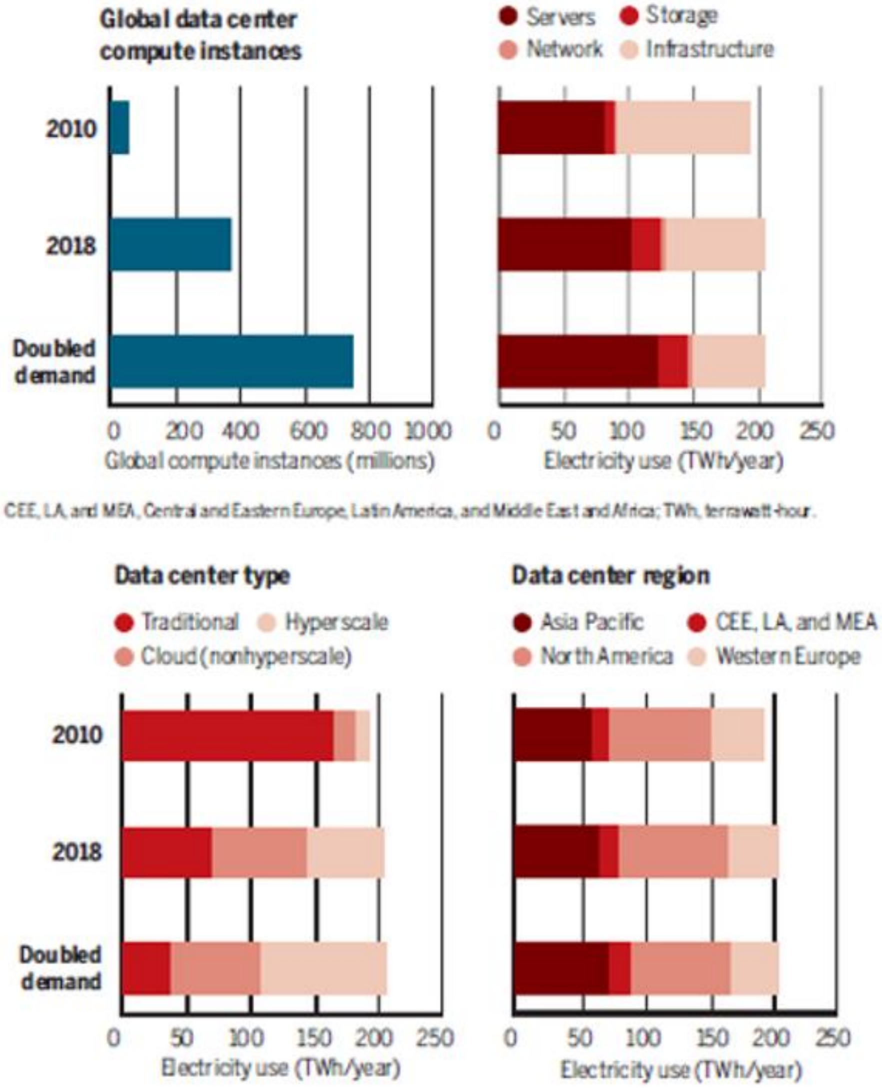
Cloud Computing Data Centres

Cloud computing is defined by Amazon as the on-demand delivery of IT resources over the Internet with pay-as-you-go pricing. Instead of buying, owning, and maintaining physical data centers and servers, users can access technology services, such as computing power, storage, and databases, on an as-needed basis from a cloud provider. (What is Cloud Computing, n.d.) The biggest cloud providers include Amazon Web Services (AWS), Microsoft Azure, and Google Cloud Platform.

Energy use in Data Centres

Defining the energy efficiency of data center equipment is extremely difficult (Fanara, 2007) because it represents a complex system with a large number of components from various research areas such as computing, networking, management, and the like. Furthermore, the lack of bottom-up information on data centre types and locations, their information technology (IT) equipment, and their energy efficiency trends make estimation of total energy demand of data centers especially challenging. A few studies attempt to do so on a smaller scale, estimating the energy consumption of cloud computing tasks (Liu et al., 2017), power modelling from a hardware-centric approach and a software-centric approach. (Dayarathna, Wen and Fan, 2016) The latest comprehensive study conducted in 2018 used the bottom-up approach and estimated that global data centre energy use amounted to 205 TWh, or around 1 percent of global electricity consumption. (Masanet et al., 2020) This figure was far more conservative than previous estimates derived from extrapolation of energy use as data centre services rises rapidly. Masanet et al. (2020) attributes the large decrease in energy intensity – energy use per compute instance, to increased server efficiencies, greater server virtualisation and decreasing energy use in data centre infrastructure systems (i.e. cooling and power provisioning). This trend can be explained by the ongoing shift from smaller traditional data centres to much more energy efficient cloud and hyperscale data centres.

Figure 5: Historical energy usage and projected energy usage



CEE, LA, and MEA, Central and Eastern Europe, Latin America, and Middle East and Africa; TWh, terawatt-hour.

(Masanet et al., 2020)

Hyperscale Data Centres

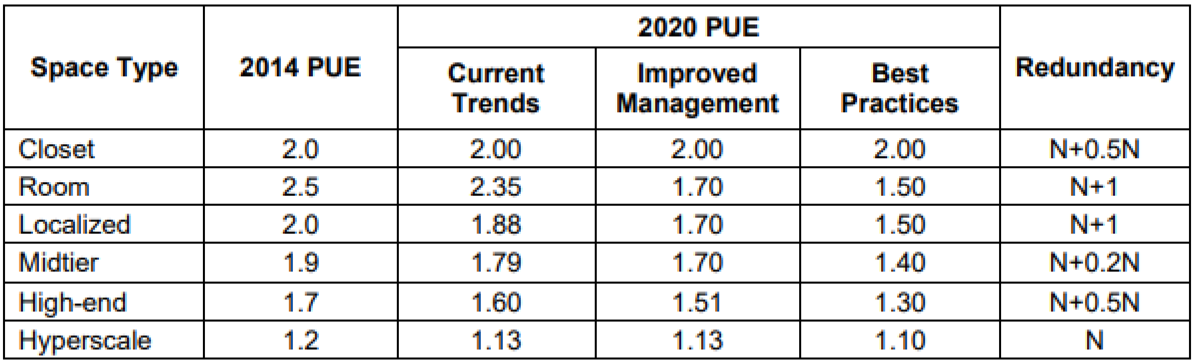
Hyperscale data centres are distinguished from non-hyperscale cloud data centres typically by their size and advanced cooling and power systems. They occupy spaces > 400,000 sqft and achieve very low PUE due to their highly-efficient infrastructure design. In recent times, hyperscale data centre sizes can range from 10 to 70 MW and occupy floor space of over a million square feet. (Data Center Frontier, 2019)

Amazon Web Services led the $130 billion global cloud infrastructure market with 32 percent market share in the fourth quarter of 2020 (Synergy Research Group, 2021), operating in 2x more regions than the next largest cloud provider which is Microsoft Azure. (Global Infrastructure Regions & AZs, n.d.)

Power Usage Effectiveness (PUE) has since become the industry standard metric to measure the efficiency of data centres. It measures the ratio of energy consumed by the tech systems over the total energy consumed by the data centre. The decreasing trend in reported PUE in data centres highlight the increasing efficiency achieved with optimisation of systems and better designed data centres to minimise the energy consumption of data centre facilities excluding those consumed by ICT. Various other metrics have also been proposed, such as the Carbon Usage Effectiveness (CUE) to assess energy source impact, Energy Reuse Factor (ERF) to track amount of energy reuse and IT Equipment Efficiency (ITEE). (Van De Voort, Zavrel, Galdiz and Hensen, 2017)

While achieving PUE of 1 is impossible, the best industry performance achieved is very close to it, with Google reporting PUE of 1.10 across all data centre operations in 2019. (Google LLC, 2021) Microsoft reported PUE of 1.3 (Microsoft Corporation, 2021) while Amazon has not disclosed their PUE performance. A US Data Centre Energy Use Report estimated the average PUE of data centres according to space type as shown in Table 1.

Table 1: PUE and Redundancy Values for Efficiency Scenarios



Space Type	2014 PUE	2020 PUE			Redundancy
		Current Trends	Improved Management	Best Practices	
Closet	2.0	2.00	2.00	2.00	N+0.5N
Room	2.5	2.35	1.70	1.50	N+1
Localized	2.0	1.88	1.70	1.50	N+1
Midtier	1.9	1.79	1.70	1.40	N+0.2N
High-end	1.7	1.60	1.51	1.30	N+0.5N
Hyperscale	1.2	1.13	1.13	1.10	N

(Shehabi et al., 2016)

Food Retail

Due to the high energy use intensity (EUI) of food retail or supermarkets in general, there are extensively literature on this topic that were guided by cost, energy resource depletion, and environmental considerations. Existing research spans energy consumption trends, carbon emissions from food retail operations, energy efficiency optimisation, technological innovation, and even non-technological drivers and barriers to adoption of better practices among food retail stores.

Energy Consumption

Several studies have quantified the energy intensity of food retail stores in the US, UK and Europe within categories defined by the size of sales area. The common trend identified was that massive-scale stores were generally more energy efficient than small-scale stores. Refrigeration was also commonly identified as the biggest source of energy consumption, estimated to consume 50-60% of the total electricity used in smaller food retail stores although large scale stores showed greater efficiency. Tassou, Ge, Hadawey and Marriott (2011) investigated the electrical energy consumption of 2570 retail food stores in the UK and found that electrical energy intensity and percentage share consumed by refrigerants were highly dependent on the sales area and varied significantly even within stores of the same category. Hyper markets with sales area between 5000 m^2 and over 10,000 m^2 had an average electrical energy consumption (EEC) of 770 kWh/m^2 where around 25%-30% was consumed by refrigeration. Supermarkets with sales area between 1400 m^2 and 5000 m^2 had an average EEC of 920 kWh/ m^2 where up to 60% was consumed by refrigeration. Ferreira, Pinheiro, de Brito and Mateus (2018) studied both energy and carbon intensity of 120 food and 122 non-food retailers and found that the energy intensity of food retailers that employed "conventional practice" ranged from 346 to 700 kWh/m^2/year and averaged at 546 kWh/m^2/year. They proposed a "best practice" energy intensity benchmark of below a 346 kWh/m^2/year threshold. Gimeno-Frontera et al. (2018) used a life-cycle approach to analyse the environmental implications of the main impact contributors to food retail store buildings which are electricity and refrigerant leakages. They found that the primary energy demand of the use phase in a reference retail building was 6240 GJ/m^2/year (1.73 TWh/ m^2/year) which accounted for 97% of the total life-cycle primary energy demand. Performance in different scenarios where the store location, opening hours and refrigerant were varied was also studied. In the United States (US), supermarkets were found consume an average of 50 kWh/sqft (538 kWh/m^2) of electricity and 50 ft^3/sqft (163.6 kWh/ m^2). (Supermarkets: An Overview of Energy Use and Energy Efficiency Opportunities, n.d.) The study also reported that, consistent with previous studies mentioned, refrigeration and lighting account for over 50% of total energy use in the average US supermarket. More recent studies suggest significant improvements in retail stores energy intensity. Another study on 593 UK supermarkets energy performance in 2015 reported lower average EUI of 444 kWh/m^2 and 524 kWh/m^2 per year for large food stores (>750m^2) and small food stores (<750m^2) respectively. (Kolokotroni et al., 2019)

Statistical Modelling

A few studies attempted to explain variances in energy performance and predict future energy demand in food retail stores. Iyer et al. (2015) proposed a methodology of disaggregating overall energy consumption of a supermarket store into weather-dependent and weather-independent component to provide better accuracy in identification of poor performing stores. They found that weather-independent loads (lights, computers, check-out tills) contribute to 45-77% of a store's total electricity consumption and can even be larger than weather-dependent loads (refrigeration and space cooling). This result warrants further study into energy efficiency improvements of weather-independent components in addition to the existing focus on improving the energy performance of weather-dependent components. Braun, Altan and Beck (2014) performed a multiple regression analysis to predict the future energy consumption of a supermarket in the UK. They derived two equation for estimation of electricity and gas consumption based on the regression analysis on consumption data, dry-bulb temperature, and relative humidity records in 2012. The results of predicted consumption in the 2040s were that electricity consumption is estimated to rise by up to 5.5% and gas consumption is estimated to fall by up to 28% due to decrease in heating. Granell, Axon, Kolokotroni and Wallom (2019) proposed a simplified statistical energy prediction model to predict the electricity daily load profile (EDLP) for new supermarket stores based on similar feature space of the store. The model best predicts EDLP during the summer for stores that only consume electricity and has an average error between 15% to 22%.

Energy Efficient Technology

The research area of energy efficiency in food retail stores is very well-studied, especially on refrigeration systems which is perceived to have the greatest potential for reducing energy consumption. Mukhopadhyay and Haberl, PhD, PE (2014) examined several energy efficiency measures (EEMS) for 1. building envelope, 2. lighting and daylighting, 3. heating, ventilation, and air conditioning (HVAC) and service hot water (SHW) systems, 4. refrigeration systems. The cumulative energy savings from combining EEMs were then assessed within categories and in totality. Their results showed that EEMs for refrigeration could provide the best energy savings of up to 16.9% through installing doors/covers on all display cases. Then followed by EEMs for HVAC systems which could provide up to 12.1% savings by implementing heat recovery from refrigeration coils. The consolidated EEMs for all the categories allowed a maximum cumulative energy consumption savings of 57.9%. Evans et al. (2016) assessed 81 technological options to reduce supermarket energy use and greenhouse gas emissions based on their emissions reduction potential, application period and financing period. Other studies performed more detailed analyses on specific energy saving technology. Ríos-Fernández (2020) found that use of higher efficiency HVAC system consisting of inverter technology in air conditioners and indoor cassette units resulted in 28% increase in coefficient of performance and 12% decrease in energy efficiency ratio during extreme conditions. Efstratiadi, Acha, Shah and Markides (2019) presented a model that compared closed-loop water-cooled refrigeration systems to air-cooled systems in the food retail industry and found that the water-cooled alternative outperformed the existing system during warm periods in the year, achieving electricity savings of up to 20% in the UK case study. Mylona, Kolokotroni, Tsamos and Tassou (2017) compared the performance of three alternative refrigeration systems to stand-alone refrigeration cabinet system in a frozen food supermarket. They found that the transcritical CO_2 booster system outperformed the other alternatives which are parallel centralised system and parallel cascade system as well as the base case of stand-alone cabinets. Mukhopadhyay and Haber, PhD, PE, BEMP (2015) assessed the performance of combined heat and power (CHP) technology in a grocery store and found 47%-54% savings in source energy over existing systems.

Barriers to Improvement

Despite the extensive literature on energy efficient technology and their potential to reduce cost of energy consumption in food retail store, many seemingly profitable strategies go unadopted. (Klemick, Kopits and Wolverton, 2017) A few studies aimed to identify the reasons for the slow adoption of energy efficient measures in this industry. Galvez-Martos, Styles and Schoenberger (2013) identified barriers to be low importance of energy costs within the total operational costs of retailers, short payback time policy, lack of control over building characteristics, lack of suppliers for novel technology and demand for technical skills and training associated with the innovative application. Klemick, Kopits and Wolverton (2017) found that uncertainty and imperfect information about the performance of new technologies, high opportunity costs of capital, and trade-offs with other valued system attributes such as reliability and customer appeal were the most pervasive potential barriers reported by US supermarket representatives interviewed in their study. Dixon-O'Mara and Ryan (2017) found that among the 42 independently owned and operated retail food outlets surveyed, economic barriers were reported most. Specifically, high initial cost of energy efficient equipment and lack of internal finance were the biggest barriers to adoption among small independent retailers. Grein and Pehnt (2011) attributed barriers that inhibit rapid adoption of load management strategies for refrigeration systems in Germany to informational barriers, strict compliance with legal cooling requirements, liability issues, lack of technical expertise, inadequate rate of return and organisational barriers. Minetto et al. (2018) considers non-technological barriers to the diffusion of energy-efficient HVAC&R solutions in the European food retail sector to be the lack of awareness of financial supports for implementation, lack of experienced trainers resulting in knowledge barrier, potential lack of enough trained technicians, and other organisational and legal barriers.

Offices

The available literature on energy use in office buildings largely focus on modelling techniques for greater accuracy in estimating and predicting energy consumption and optimising energy efficiency. Recent studies however are pre-dominated by research on the impact of changing climate on the energy consumption of buildings which is expected to be a going concern in the future. Studies on factors impacting energy consumption and the impact of occupants on overall energy consumption are also reviewed.

Energy Modelling

Various models have been proposed while others applied novel techniques to estimate and predict energy consumption in office buildings. Korolija, Zhang, Marjanovic-Halburd and Hanby (2013) proposed regression models to predict office building annual heating, cooling and auxiliary energy demands for different HVAC systems and evaluated their performance using a simulating software, EnergyPlus. Shi, Liu and Wei (2016) used the approach of echo state networks (ESNs) to predict energy consumption in office buildings, where they developed novel reservoir topologies to predict the energy consumption of rooms based on their function. Amasyali and El-Gohary (2018) used a hybrid machine-learning and data-mining approach to develop prediction models for energy consumption of office buildings. Liu, Yang and Yang (2019) developed a prediction model for buildings system energy consumption such as lighting, outlet and air conditioning, using time series analysis methods. Other studies modelled the impact of specific factors on the energy consumption of office buildings, such as orientation and building characteristics (Vasov et al., 2018), use of small power equipment (Menezes et al., 2014), building airtightness (Liu, Li, Yao and Cao, 2020) as well as use of single and multiple energy retrofit measures. (Chidiac, Catania, Morofsky and Foo, 2011)

Climate Impact

The effect of climate change on office buildings energy consumption has been studied for countries. Kolokotroni, Ren, Davies and Mavrogianni (2012) investigated the impact on present and future energy consumption for office buildings in London’s urban heat island. They found that between 2000 and 2050, electric cooling energy consumption is between 23% and 30% more in 2050 and gas heating energy consumption is reduced by almost 40% in 2050. The effect was also studied in Japan which found a similar results of increased cooling load and decreased heating load for office buildings between 1990s and 2040s. (Shibuya and Croxford, 2016) A study on the effects experienced for office buildings in different climate zones in China, in addition to similar results on heating and cooling loads, found that the dry bulb temperature is the dominant climatic parameter affecting building heating loads and can be used in regression models to predict heating energy consumption.

Other research also studied the impact of energy reduction measures such as improving building envelop which can provide 45% of energy savings (Charles, Maref and Ouellet-Plamondon, 2019), static and dynamic shading systems (De Luca, Voll and Thalfeldt, 2018), and energy efficient glass that could reduce building electricity costs by 45%-53% (Graiz and Al Azhari, 2019).

Chapter 4: Methodology

Calculation of Energy Demand

Amazon’s total energy demand would mostly be determined based on a bottom-up calculation of estimated energy consumption in each key operation. Sources of energy consumption and estimation of demand would be informed by the literature review where available and otherwise informed by reputable sources such as government agencies or industry consultancy experts. While still in the early phases of deployment, this study includes the energy demand expected from the full deployment of electric delivery vans by 2030 which is likely to be realised.

Logistics Centres

The energy demand of Amazon’s logistics centre was estimated by calculating the energy demand of the building systems and the energy demand of the autonomous mobile robots that are employed in the fulfilment centres. For the buildings systems, the average energy intensity of typical refrigerated and non-refrigerated warehouses in the US was multiplied by the floor space of the respective facilities according to a logistics and supply chain consulting firm, MWPVL International Inc. (MWPVL International Inc., 2021)

Electric Vehicles

As the technical specifications of the Rivian electric vans are unavailable, a similar van will be used as reference. The technical specifications of the Mercedes-Benz vans are available and obtained from the Mercedes-Benz website. The last-mile delivery model proposed by MWPVL International will be used to estimate the energy demand from the electric vans.

Data Centres

Amazon’s cloud data centres (AWS) energy consumption will be estimated as their market share equivalent of the total energy consumed by cloud data centres in the world and adjusted for their expected lower than industry average PUE. AWS commanded a global market share of 32 percent in 2020 and the total energy use of cloud data centres was 205 TWh. This paper assumed the best-case scenario where AWS is operating at the lowest achieved PUE level of 1.1 and that the industry standard PUE is 1.67.

Supermarkets

The energy demand of Amazon’s Whole Foods Market stores will be estimated using supermarket energy consumption data published by EnergyStar, a program backed by the US government, and multiplied by the total floorspace occupied by grocery chain.

Offices

Country-specific energy use intensity (EUI) of offices buildings will be obtained from available literature and official statistics reported, otherwise a regional or global average EUI will be used to estimate the energy demand of offices in the country without published EUI figures. The EUI values are multiplied by the floor space of corresponding office buildings to derive the total energy demand.

Renewable Energy Project Testing

RETScreen4, a renewable energy project testing software, was used to size the capacity of solar PV or onshore wind farm required to match the total energy demand estimated.

The potential site location for a hypothetical solar PV farm was narrowed down to the USA since it is where most of Amazon's operations are based in and existing renewable projects are located. The online resource, Global Solar Atlas, was used to identify regions in the US with the highest solar irradiation levels which was within the state of California. The location of Palm Springs was selected due to high solar irradiation levels that covers a large part of the area, which is required for a massive PV farm. The PV panels selected for the project was monocrystalline silicon type and had a power rating of 300W.

The potential site location for a hypothetical wind farm was once again narrowed down to the USA since it is where most of Amazon's operations are based in and existing renewable projects are located. The online resource, Global Wind Atlas, was used to identify regions in the US with the highest wind speeds. Due to the popularity of the region for wind farm projects and the fact that Amazon has existing wind farms in that region, the state of Texas was selected as a potential region. From the RETScreen climate database, the location was further narrowed down to Abilene which had the best wind prospect among the available locations in the database. The wind turbines selected for the project was the Vestas onshore wind turbine of 3.0 MW power rating. Wind shear exponent value was taken from the results for annual average wind shear measured by sensors placed between 40m and 80m at projects in Big Spring, Texas. (Smith et al., 2002) The values selected for array losses, airfoil losses, miscellaneous losses and availability were informed by RETScreen suggestions and assumed the best reasonable case scenario for large scale onshore wind projects.

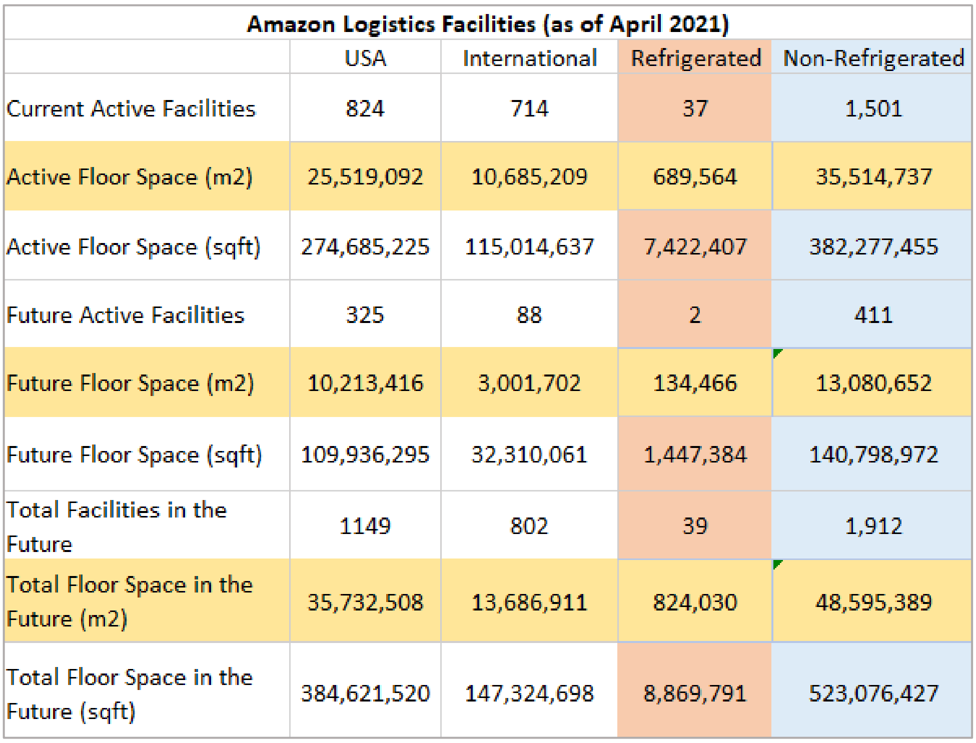
Chapter 5: Analysis

Energy Demand

E-Commerce Logistics Energy Demand

A detailed listing of Amazon's logistics facilities is provided by MWPVL International – a global Supply Chain, Logistics and Distribution Consulting firm. (Wulfraat, 2021) Table 2 summarises the information and categorises them into refrigerated and non-frigerated facilities for greater accuracy in calculation of energy demand. Refrigerated facilities are assumed to be Amazon Pantry/ Fresh Food fulfilment centres and Whole Foods Retail Grocery distribution centres, while the rest of the facilities are treated as non-refrigerated facilities.

Table 2: Summary of Amazon's logistics facilities



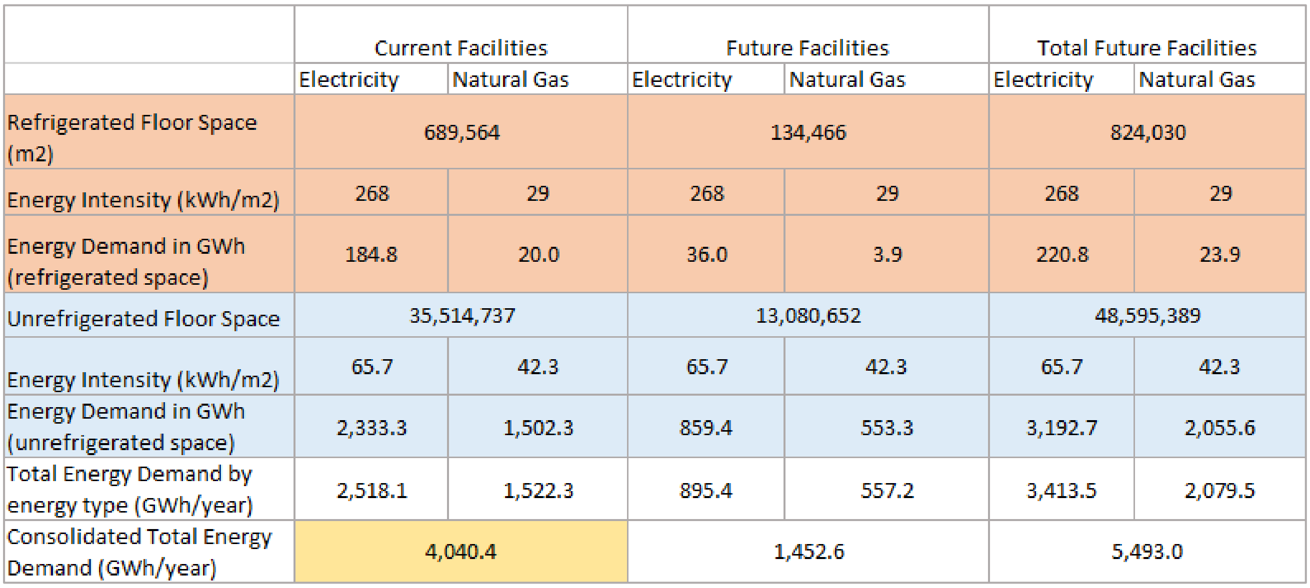
Amazon Logistics Facilities (as of April 2021)

	USA	International	Refrigerated	Non-Refrigerated
Current Active Facilities	824	714	37	1,501
Active Floor Space (m2)	25,519,092	10,685,209	689,564	35,514,737
Active Floor Space (sqft)	274,685,225	115,014,637	7,422,407	382,277,455
Future Active Facilities	325	88	2	411
Future Floor Space (m2)	10,213,416	3,001,702	134,466	13,080,652
Future Floor Space (sqft)	109,936,295	32,310,061	1,447,384	140,798,972
Total Facilities in the Future	1149	802	39	1,912
Total Floor Space in the Future (m2)	35,732,508	13,686,911	824,030	48,595,389
Total Floor Space in the Future (sqft)	384,621,520	147,324,698	8,869,791	523,076,427

(Wulfraat, 2021)

Energy consumption data are obtained from Orlando Utilities Commission, a municipally-owned public utility operating in Florida, USA. They estimated that non-refrigerated warehouses in the US use about 65.7 kWh/m^2 (6.1 kWh/sqft) of electricity and 42.3 kWh/m^2 (13,400 Btu/sqft) of natural gas per year, while refrigerated warehouses use 268.0 kWh/m^2 (24.9 kWh/sqft) of electricity and 29.0 kWh/m^2 (9,200 Btu/sqft) of natural gas per year. (Warehouses, n.d.) These energy intensity values are multiplied with the floor space of respective facilities to determine the annual energy consumption.

Table 3: Estimated Energy Demand (Logistics Facilities)



	Current Facilities		Future Facilities		Total Future Facilities	
	Electricity	Natural Gas	Electricity	Natural Gas	Electricity	Natural Gas
Refrigerated Floor Space (m2)	689,564		134,466		824,030	
Energy Intensity (kWh/m2)	268	29	268	29	268	29
Energy Demand in GWh (refrigerated space)	184.8	20.0	36.0	3.9	220.8	23.9
Unrefrigerated Floor Space	35,514,737		13,080,652		48,595,389	
Energy Intensity (kWh/m2)	65.7	42.3	65.7	42.3	65.7	42.3
Energy Demand in GWh (unrefrigerated space)	2,333.3	1,502.3	859.4	553.3	3,192.7	2,055.6
Total Energy Demand by energy type (GWh/year)	2,518.1	1,522.3	895.4	557.2	3,413.5	2,079.5
Consolidated Total Energy Demand (GWh/year)	4,040.4		1,452.6		5,493.0	

The current estimated energy consumption for Amazon's logistics facilities is 4.04 TWh annually and could rise by 36% to 5.493 TWh in the future.

In addition to logistics facilities, the intra-logistics system that Amazon employs in their fulfilment centres would present additional energy demand on top of normal warehouse operations and requirements. Amazon reportedly has over 200,000 robots in their Robotic Mobile Fulfilment System that operates both storage and retrieval functions autonomously. (O'Brien, 2019) A technical specifications of the robots were detailed in a report conducted by Lasmana (2018) which revealed that the KIVA robot was powered by four 12 V 28Ah lead acid batteries connected in series. They operated for one 8-hour shift during normal periods and 2 or 3 shifts during peak periods. MWPVL International also notes that the KIVA robots have a 5-minutes recharge time and that 5% of robots are out of commission at any time due to recharging demands. (Wulfraat, n.d.) Assuming a lead-acid battery discharge of 50% and the average daily operation duration for the Kiva robot to be 2 8-hour shifts, the energy demand of the Kiva robots is estimated as follows.

Estimated annual electricity demand of Kiva robots =

total battery capacity x depth of discharge x hours of operation per day x number of days in a year x number of robots x percentage of robots in operation at any given time

= (4 x 12 V x 28 Ah) x 0.5 x 16 hours/day x 365 days x 200,000 x 0.95

*= **0.746 TWh per year***

The additional energy demand from Kiva systems would bring the total estimated energy demand from Amazon's logistics operations to **4.786 TWh** per year.

Electric Vehicles Energy Demand

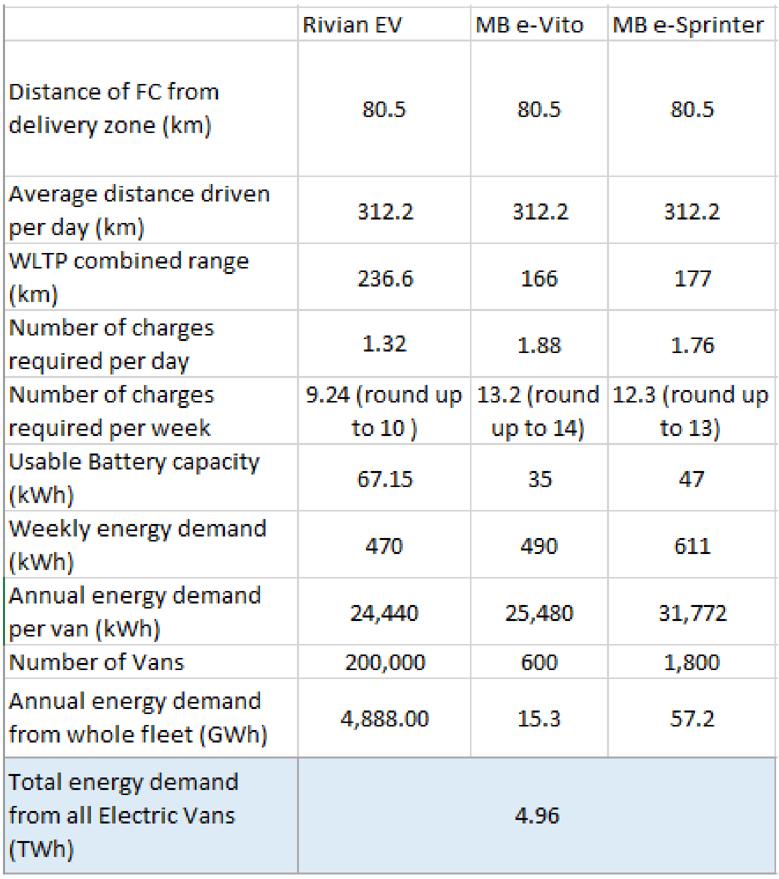
Amazon's Rivian electric delivery vans are currently under development and technical specifications are largely unknown. However, it is speculated that the Rivian vans will be available in 3 sizes – 500, 700 and 900 cubic ft, with the largest van having a minimum range of 150 miles. (Markus, 2021) Based on this information, the specifications of comparable vehicles will be used as a reference to estimate the energy demand from deployment of the Rivian vans.

The Fiat E-Ducato van was selected as a comparable van for reference based on size and range. The technical specifications of reference van are provided in Appendix 3. The selected model has a battery size of 79 kWh, with a usable capacity of 67.15 kWh. (Fiat e-Ducato, n.d.)

According to MWPVL International, Amazon's Last Mile delivery facilities are designed to service a 45 mile radius. (Wulfraat, 2021) Based on their last-mile delivery models, the average distance driven in a typical day is 194 miles (312.2 km) for a scenario where the fulfilment centre is 50 miles (80.5 km) away from the customer delivery zone. The number of charges required per day is calculated by dividing the daily driving distance by the WLTP combined range reported. The daily energy demand for the van is then calculated by multiplying the daily number of charges by the usable battery capacity of the van. It should be noted that where the daily number of charges is not a whole number, the weekly number of charges would be computed instead and rounded up to the nearest whole number.

Amazon has also announced the order of 1,800 Mercedes-Benz Electric delivery vans – 600 units of the e-Vito model and 1,200 units of the e-Sprinter model. (Lambert, 2020) The technical specifications of the vans are listed in Appendix 4 and 5. The same approach and model used for the Rivian vans is applied for estimating the energy demand of these vans.

Table 4: Estimated Energy Demand (EV)



	Rivian EV	MB e-Vito	MB e-Sprinter
Distance of FC from delivery zone (km)	80.5	80.5	80.5
Average distance driven per day (km)	312.2	312.2	312.2
WLTP combined range (km)	236.6	166	177
Number of charges required per day	1.32	1.88	1.76
Number of charges required per week	9.24 (round up to 10)	13.2 (round up to 14)	12.3 (round up to 13)
Usable Battery capacity (kWh)	67.15	35	47
Weekly energy demand (kWh)	470	490	611
Annual energy demand per van (kWh)	24,440	25,480	31,772
Number of Vans	200,000	600	1,800
Annual energy demand from whole fleet (GWh)	4,888.00	15.3	57.2
Total energy demand from all Electric Vans (TWh)	4.96		

AWS Data Centres Energy Demand

With the lack of ground information on Amazon's cloud data centre operations, a top-down approach will be used to estimate AWS energy demand. Based on the study on data centre energy consumption by Masanet et al. (2020), the data centre industry consumed around 205 TWh in 2018. Traditional data centre energy consumption was around 65 TWh, which means that cloud data centres, including hyperscale, was estimated to consume about 140 TWh in 2018. The literature review suggests that energy consumption of this industry can be expected to remain relatively constant as energy efficiency is constantly improving which is large enough to offset increase in operation demand for cloud data centres over the next few years. Therefore, it is reasonable to assume that in 2021 and the near future, the cloud-based data centre industry will continue to consume around 140 TWh annually. AWS market share in the global cloud data centre industry was 32% in the last quarter of 2020. (Richter, 2021) Assuming that energy demand per dollar revenue is constant, AWS energy demand was estimated as their market share proportion of the total energy consumed by global cloud data centres.

AWS estimated energy demand = 32% x 140 TWh = 44.8 TWh

As AWS operates a number of hyperscale data centres, their overall PUE is expected to be significantly lower than the industry average of 1.67 and closer to their direct industry competitors – Microsoft and Google, who reported PUE levels of 1.3 and 1.10 respectively. This paper will assume the best-case scenario where AWS can achieve the lowest PUE level of 1.10. Taking into account the superior energy efficiency performance of AWS, an adjusted estimate of energy demand by AWS was calculated.

PUE adjusted energy demand of AWS = (1.10/1.67) x 44.8 TWh = 29.5 TWh

Amazon's Whole Foods Market Energy Demand

As of February 2021, Amazon reportedly has 503 Whole Foods store in the US. (Number of Whole Foods in USA | 2021 Store Location Analysis, 2021) The average size of Whole Foods stores was estimated as 40,000 sqft (3716 m^2) in 2017. (Coppola, 2020) Due to the lack of more recent data, this paper will assume that the average store size has remained the same as of April 2021. The average energy intensity of supermarkets in the US, as reported by US government-backed Energy Star program, will be used to estimate the total energy demand of the Whole Foods stores.

Annually, the supermarkets are expected to consume around 50 kWh/sqft of electricity and 50 cubic ft/sqft of natural gas. (Supermarkets: An Overview of Energy Use and Energy Efficiency Opportunities, n.d.)

Table 5: Estimated Energy Demand (Whole Foods Market)

Whole Foods Market		
Number of Stores	503	
Size	Average 40,000 sqft (3716 m²) Total Store Area: 503 x 40,000 = 20,120,000 sqft (1,869,148 m²)	
Energy Consumption	**Electricity:** 50 kWh/sqft/year	**Natural Gas:** 50 cubic feet/sqft/year
	= 538 kWh/m²/year	= 54.705 MJ/sqft/year = 15.196 kWh/sqft/year = 163.6 kWh/m²/year
Total Energy Demand	**1.006 TWh/year**	**0.306 TWh/year**

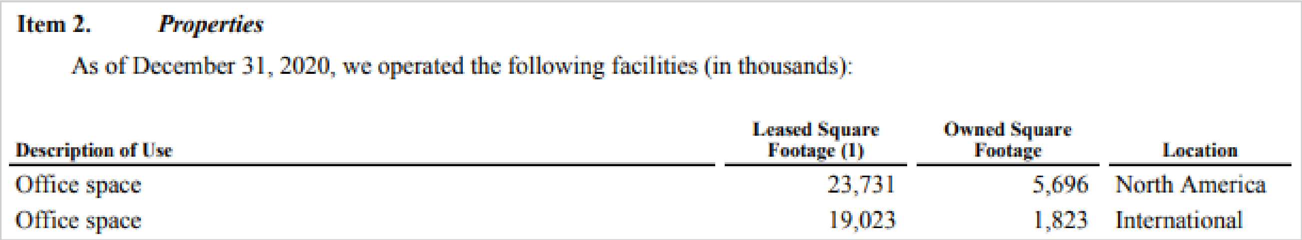
Assuming that only electricity was used to meet the total energy demands of the Whole Foods stores, about **1.312 TWh** of electricity would be required annually.

Amazon’s 2020 Annual Report disclosed 21,988,000 sqft of physical stores own or leased by them. (Amazon.com, Inc., 2021) The Whole Foods stores considered in this paper accounts for 91.5% of their physical stores, where the other facilities included Amazon Fresh stores, physical bookstores, and retail stores.

Office Energy Demand

According to Amazon’s 2020 Annual Report, they occupied a total of 4,670,515 m² (50,273,000 sqft) in office space which was categorised under North America - 2,733,858 m² (29,427,000 sqft) and International - 1,936,657 m² (20,846,000 sqft). (Amazon.com, INC., 2021)

Table 6: Amazon's Offices



Item 2. ***Properties***

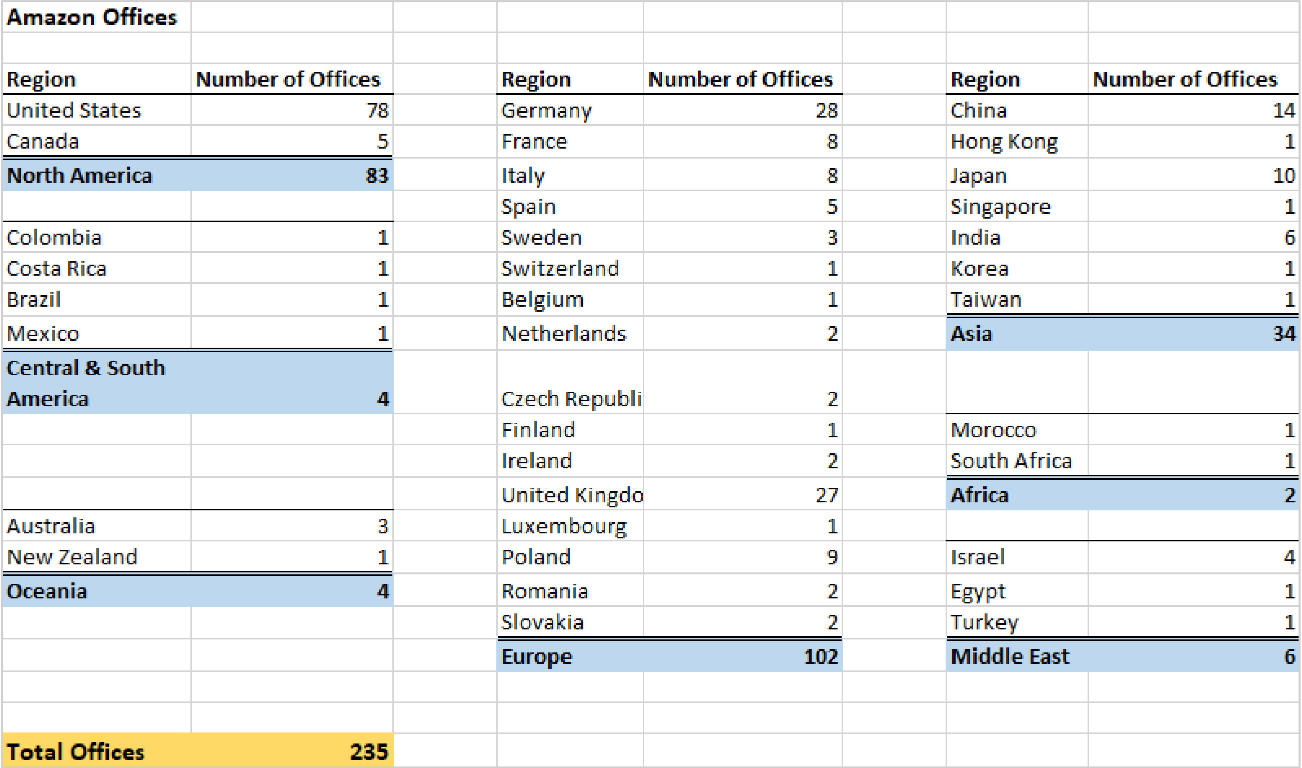
As of December 31, 2020, we operated the following facilities (in thousands):

Description of Use	Leased Square Footage (1)	Owned Square Footage	Location
Office space	23,731	5,696	North America
Office space	19,023	1,823	International

(Amazon.com, INC., 2021)

Data on Amazon's office locations was obtained from an enterprise intelligence company, Craft, which show that Amazon has 235 office locations over 36 countries.

Table 7: Amazon's Office Locations



Amazon Offices					
Region	**Number of Offices**	**Region**	**Number of Offices**	**Region**	**Number of Offices**
United States	78	Germany	28	China	14
Canada	5	France	8	Hong Kong	1
North America	**83**	Italy	8	Japan	10
		Spain	5	Singapore	1
Colombia	1	Sweden	3	India	6
Costa Rica	1	Switzerland	1	Korea	1
Brazil	1	Belgium	1	Taiwan	1
Mexico	1	Netherlands	2	**Asia**	**34**
Central & South America	**4**	Czech Republi	2		
		Finland	1	Morocco	1
		Ireland	2	South Africa	1
		United Kingdo	27	**Africa**	**2**
Australia	3	Luxembourg	1		
New Zealand	1	Poland	9	Israel	4
Oceania	**4**	Romania	2	Egypt	1
		Slovakia	2	Turkey	1
		Europe	**102**	**Middle East**	**6**
Total Offices	**235**				

(Amazon headquarters and office locations, n.d.)

A literature review was conducted to compile the energy intensity of office buildings in various locations where available.

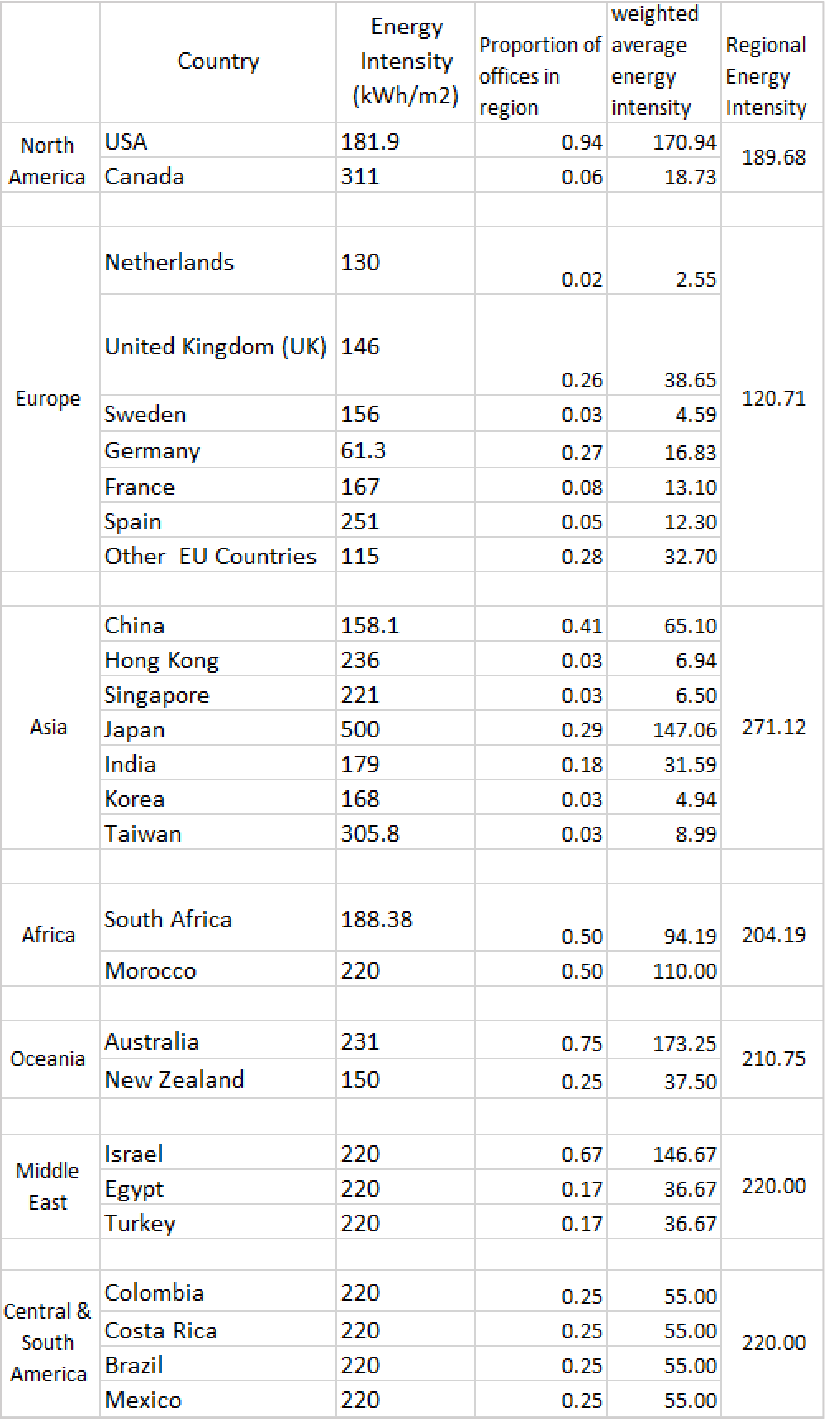
Table 8: Energy Intensity of Office Buildings by Country)

Region	Country/ Regional average	Energy Intensity (kWh/m2)	Description	Reference Literature
North America	USA	181.9	Administrative or professional office site electricity consumption in 2012 was 16.9 kWh/sqft	Commercial Buildings Energy Consumption Survey (CBECS) (2016)
	Canada	311	Energy intensity of office buildings (non-medical) was 1.12 GJ/m2 in 2014	Energy intensity by building type, 2014 (2016)
Europe	Netherlands	130	Energy consumption of offices in 2018	Electricity Consumption in Offices (2021)
	United Kingdom (UK)	146	Energy consumption per m2 of offices in 2018	Electricity Consumption in Offices (2021)
	Sweden	156	Energy consumption per m2 of offices in 2018	Electricity Consumption in Offices (2021)
	Germany	61.3	Energy consumption per m2 of offices in 2005	Electricity Consumption in Offices (2021)
	France	167	Energy consumption per m2 of offices in 2018	Electricity Consumption in Offices (2021)
	Spain	251	Energy consumption per m2 of offices in 2018	Electricity Consumption in Offices (2021)
	EU Average	115	Energy consumption per m2 of offices within the European Union in 2018	Electricity Consumption in Offices (2021)
Asia	China	158.1	Energy consumption per unit building area of commercial buildings in China in 2015	Huo et al. (2019)
	Hong Kong	236	Energy use intensity of commercial office buildings in Hong Kong in	Jing et al. (2017)
	Singapore	221	Average Energy use intensity of office buildings in 2017	BCA Building Energy Benchmarking Report (2018)
	Japan	500	Estimated Energy use intensity of office buildings in Tokyo	Hirano et al. (2017)
	India	179	EPI benchmarks for office buildings in composite climate zone	Energy Benchmarks for Commercial Buildings (n.d.)
	Korea	168	Mean annual total energy consumption of office buildings in 2015	Ahn, Shin and Park (2019)
	Taiwan	305.8	Average Energy usage intensity per floor in Taipei City	Lin, Wu and Lai (2013)
Africa	South Africa	188.38	Energy use intensity of office buildings between October 2006 and September 2007	Martin (2013)
Oceania	Australia	231	Projected Average Energy intensity of whole office buildings in 2020	pitt&sherry, BIS Shrapnel and Exergy Pty Ltd (2012)
	New Zealand	150	Electricity Intensity of Office Buildings in New Zealand in 2008	McDonagh (2011)
Global	Global Average	220	Global non-residential building sector energy intensity in 2014	Dean, Dulac, Petrichenko and Graham (2016)

The weighted average energy intensity for each region was calculated by multiplying the country's energy intensity by their proportion of office buildings in the region. The regional average energy intensity or global average energy intensity is used in cases where country-specific data is unavailable in existing literature.

Weighted average energy intensity of region = ∑ (energy intensity of country x (number of offices in that country/ total number of offices in that region))

Table 9: Weighted Average Energy Intensity of Regions



	Country	Energy Intensity (kWh/m2)	Proportion of offices in region	weighted average energy intensity	Regional Energy Intensity
North America	USA	181.9	0.94	170.94	189.68
	Canada	311	0.06	18.73	
Europe	Netherlands	130	0.02	2.55	120.71
	United Kingdom (UK)	146	0.26	38.65	
	Sweden	156	0.03	4.59	
	Germany	61.3	0.27	16.83	
	France	167	0.08	13.10	
	Spain	251	0.05	12.30	
	Other EU Countries	115	0.28	32.70	
Asia	China	158.1	0.41	65.10	271.12
	Hong Kong	236	0.03	6.94	
	Singapore	221	0.03	6.50	
	Japan	500	0.29	147.06	
	India	179	0.18	31.59	
	Korea	168	0.03	4.94	
	Taiwan	305.8	0.03	8.99	
Africa	South Africa	188.38	0.50	94.19	204.19
	Morocco	220	0.50	110.00	
Oceania	Australia	231	0.75	173.25	210.75
	New Zealand	150	0.25	37.50	
Middle East	Israel	220	0.67	146.67	220.00
	Egypt	220	0.17	36.67	
	Turkey	220	0.17	36.67	
Central & South America	Colombia	220	0.25	55.00	220.00
	Costa Rica	220	0.25	55.00	
	Brazil	220	0.25	55.00	
	Mexico	220	0.25	55.00	

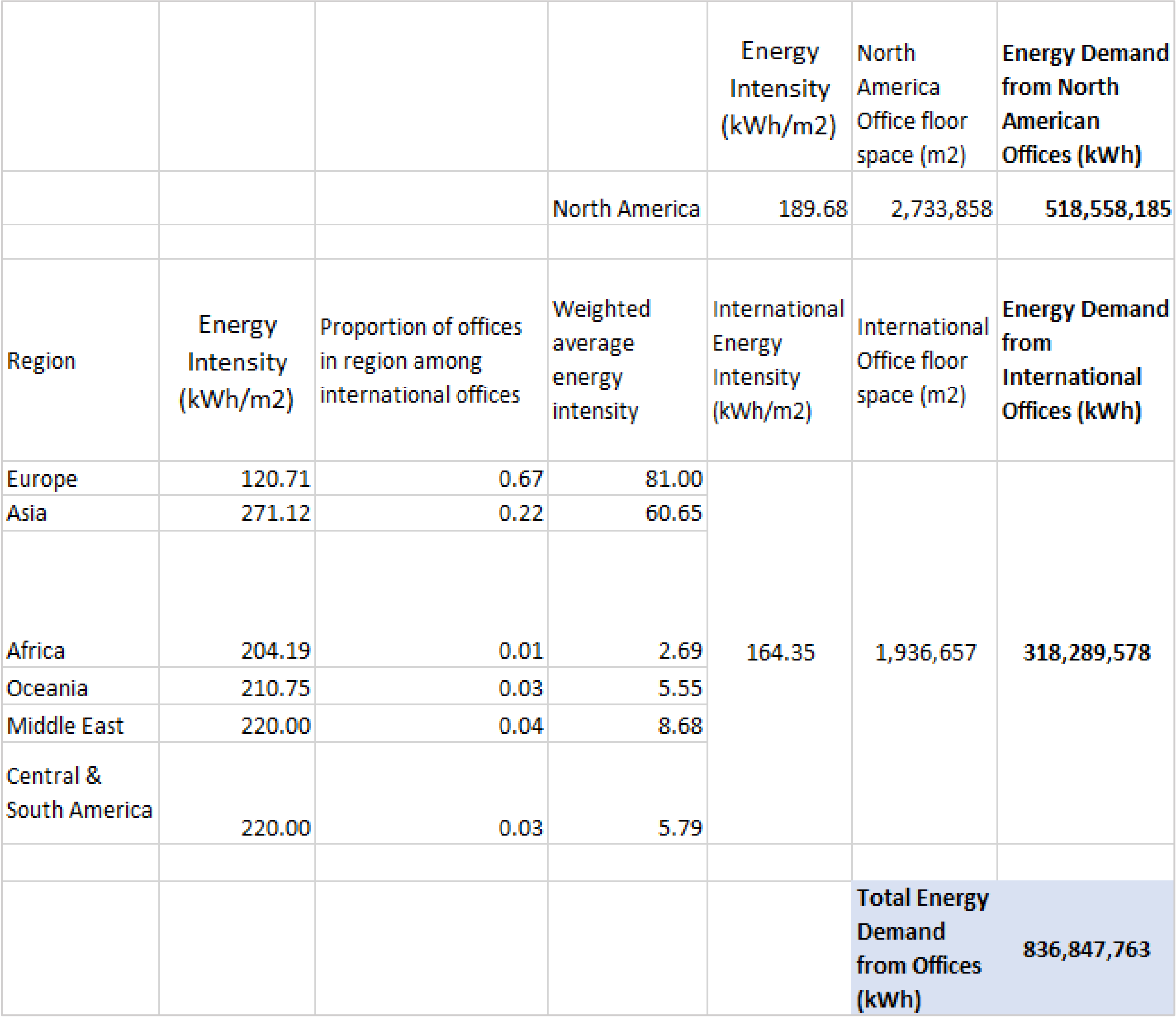
The weighted average energy intensity was then calculated for North America and International offices.

> *Energy intensity (North America) = (US energy intensity x (number of US offices/ total number of office in North America)) + (Canada energy intensity x (number of offices in Canada/ total number of offices in North America))*

Energy intensity (International) = ∑ (energy intensity of international region x (number of offices in that international region/ total number of international offices))

The total energy demand from offices was calculated by multiplying the energy intensity and floor space for North America and International offices.

Table 10: Estimated Energy Demand (Offices)

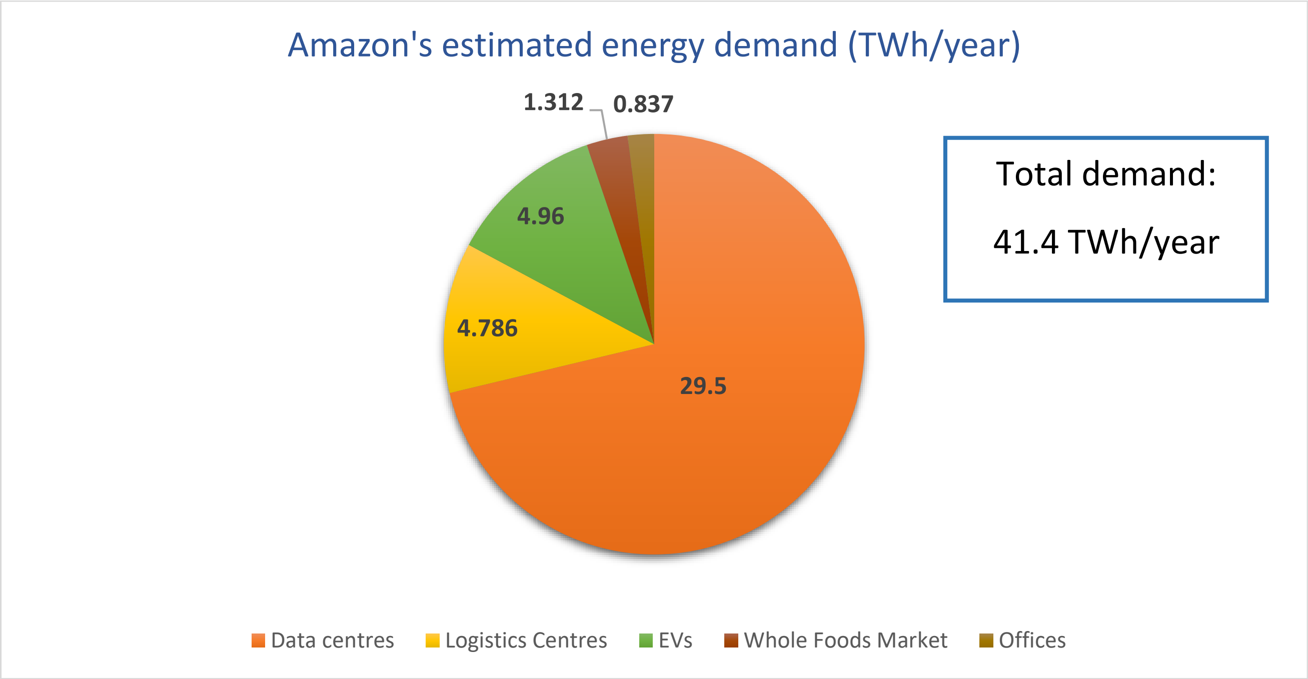


				Energy Intensity (kWh/m2)	North America Office floor space (m2)	**Energy Demand from North American Offices (kWh)**
			North America	189.68	2,733,858	**518,558,185**
Region	Energy Intensity (kWh/m2)	Proportion of offices in region among international offices	Weighted average energy intensity	International Energy Intensity (kWh/m2)	International Office floor space (m2)	**Energy Demand from International Offices (kWh)**
Europe	120.71	0.67	81.00	164.35	1,936,657	**318,289,578**
Asia	271.12	0.22	60.65			
Africa	204.19	0.01	2.69			
Oceania	210.75	0.03	5.55			
Middle East	220.00	0.04	8.68			
Central & South America	220.00	0.03	5.79			
					Total Energy Demand from Offices (kWh)	**836,847,763**

Total Energy Demand

This paper estimates that Amazon would require at least 41.4 TWh of energy per year to power its key energy consuming operations as summarised in the graph below. This is based on the assumption that electric heating is used in place of gas heating.

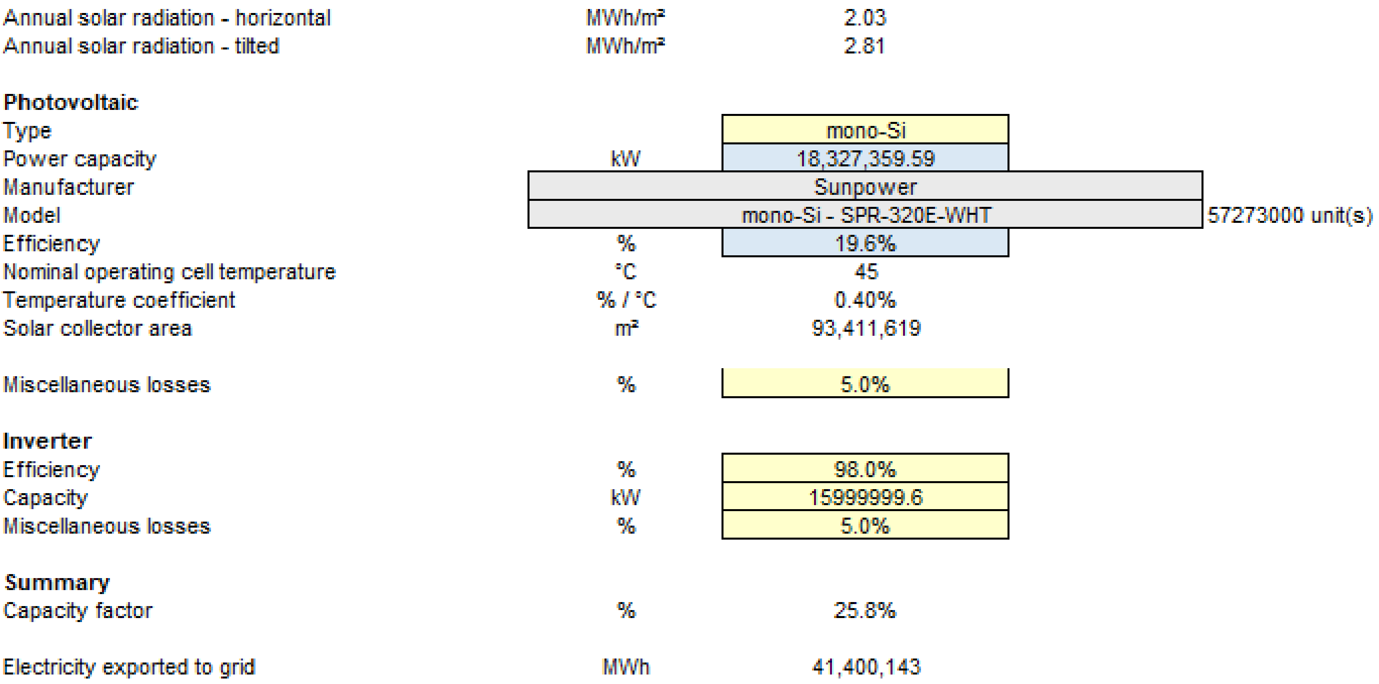
Figure 6: Estimated Total Energy Demand



RETScreen Projects

Solar PV Farm Project in Palm Springs, California, USA

Figure 7: Solar PV project results



Annual solar radiation - horizontal	MWh/m²	2.03	
Annual solar radiation - tilted	MWh/m²	2.81	
Photovoltaic			
Type		mono-Si	
Power capacity	kW	18,327,359.59	
Manufacturer		Sunpower	
Model		mono-Si - SPR-320E-WHT	57273000 unit(s)
Efficiency	%	19.6%	
Nominal operating cell temperature	°C	45	
Temperature coefficient	% / °C	0.40%	
Solar collector area	m²	93,411,619	
Miscellaneous losses	%	5.0%	
Inverter			
Efficiency	%	98.0%	
Capacity	kW	15999999.6	
Miscellaneous losses	%	5.0%	
Summary			
Capacity factor	%	25.8%	
Electricity exported to grid	MWh	41,400,143	

The results showed that a solar PV project of around 16 GW power capacity would be required to meet the estimated total energy demand of Amazon's key operations. This would require around 57,273,000 units of monocrystalline silicon solar panels operating at 19.6% efficiency with an overall capacity factor of 25.8 percent.

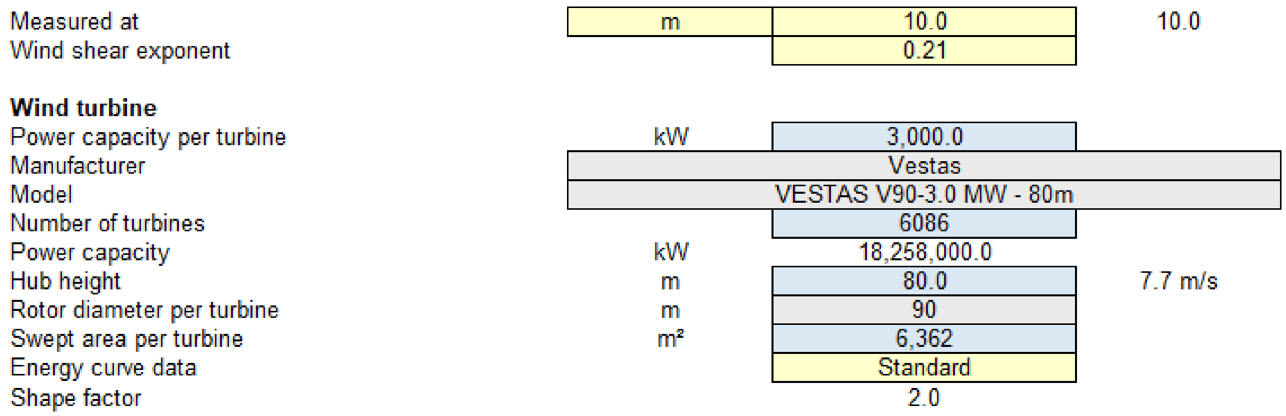
The results show that approximately 93.4 km^2 of land area would be needed for the solar collectors. However, a solar PV installation site includes the footprint of all areas directly transformed or impacted by the installation during its lifecycle. These can include the use of ancillary facilities, publicly owned-roads, pipelines, transmission corridors, and communications sites which add to the total footprint of the solar PV project. (Hernandez, Hoffacker and Field, 2014) A survey conducted on the nominal capacity-based land use efficiency (LUE) of utility-scale solar energy installations in California estimated an LUE of 35.1 W/m^2 for PV installations. (Hernandez, Hoffacker and Field, 2014) Based on this LUE estimate, the land required for this solar PV project with a nominal capacity of 18.3 GW is about 522 km^2.

This land area is comparable to the size of a small island and almost 4 and a half times the size of Dublin city. (O'Beirne Ranelagh, n.d.) Building such a project would likely take up 0.12% of California's land area. (Morgan and McNamee, n.d.)

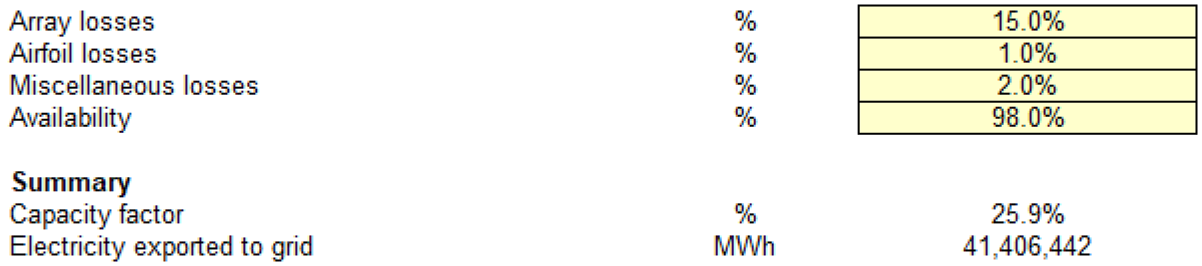
The solar panels alone would cost at least £16.2 billion ($22.5 bn) at £283 ($392.66) per unit but could export $7.02 trillion worth of electricity annually at a rate of 17.92 cents per kWh. (SunPower SPR-320NE-WHT-D 320 Watt Solar Panel Module, n.d.; Electric Power Monthly - U.S. Energy Information Administration (EIA), 2021) Furthermore, the cost of solar panels represents a mere 5.8% of Amazon's net sales in 2020. (Amazon.com, Inc., 2021)

Onshore Wind Farm Project in Abilene, Texas, USA

Figure 8: Onshore Wind project results



Measured at	m	10.0	10.0
Wind shear exponent		0.21	
Wind turbine			
Power capacity per turbine	kW	3,000.0	
Manufacturer		Vestas	
Model		VESTAS V90-3.0 MW - 80m	
Number of turbines		6086	
Power capacity	kW	18,258,000.0	
Hub height	m	80.0	7.7 m/s
Rotor diameter per turbine	m	90	
Swept area per turbine	m²	6,362	
Energy curve data		Standard	
Shape factor		2.0	



Array losses	%	15.0%
Airfoil losses	%	1.0%
Miscellaneous losses	%	2.0%
Availability	%	98.0%
Summary		
Capacity factor	%	25.9%
Electricity exported to grid	MWh	41,406,442

The results showed that an onshore wind project of around 18.3 GW power capacity would be required to meet the estimated total energy demand of Amazon's key operations. This would require 6,086 units of 3 MW wind turbines operating with an overall capacity factor of 25.9%. Based on conventional spacing of 7 times the rotational diameter of the wind turbines used, the land area required for this project is at least 2,354 km^2. (Meyers and Meneveau, 2012) This land area is comparable to the size of a small country and almost 3 times the size of New York city. (Lankevich, n.d.) Building such a project would likely take up 0.34% of Texas' land area. (Wooster, Reddick and McNamee, 2021)

The wind turbines alone would cost €4.56 million ($5.52 m) at €750 per piece but could export $7.02 trillion worth of electricity annually at a rate of 17.92 cents per kWh. (Ankersmit, n.d.; Electric Power Monthly - U.S. Energy Information Administration (EIA), 2021) Furthermore, the cost of wind turbines represents around 0.0014%, an almost insignificant amount, of Amazon's net sales in 2020. (Amazon.com, Inc., 2021)

If Amazon were a country, they would have an energy intensity of 0.107 kWh/dollar of revenue (0.3852 MJ/$). They would also rank as the 2nd most energy efficient country out of 189 countries in 2015, beating even China's energy intensity by more than 2 times. (Energy intensity by country, n.d.) Amazon employed 1.13 million people worldwide in 2020, so their energy per capita is 36.6 MWh which is once again ranked 2nd in world (only topped by Iceland) and more than 3 times that of North America based on 2018 data. (Electric power consumption (kWh per capita), 2014; Data & Statistics - IEA, n.d.)

Chapter 6: Discussion and Conclusions

This paper provided a reasonable estimate of Amazon's total energy demand which amounted to 41.4 TWh per year. The major sources of energy consumption were accounted for by calculating the energy demand from each of Amazon's key operations – e-commerce, AWS cloud service, offices, Whole Foods Market grocery chain and the future deployment of electric delivery vans. The RETScreen software showed that a solar PV project of about 16 GW capacity and an onshore wind project of about 18.3 GW capacity would be sufficient to provide at least 41.4 TWh of electricity annually. Since Amazon has the financial capacity to fund both the renewable energy projects and there is sufficient land available for construction of the projects, this paper concludes that it is highly feasible for Amazon to achieve their commitment of using 100% renewable energy. This paper also notes that despite the massive global footprint that Amazon occupies, the company is extremely energy efficient when compared to other countries by energy intensity and energy per capita. This could be attributed to the fact that a massive proportion of Amazon's revenue-generating operation occurs virtually.

However, the analysis in this paper is limited by the use of secondary data and simple methods to estimate energy consumption. Furthermore, the scope of operations considered does not include other major sources of energy demand such as fossil fuel-powered road and air freight used in Amazon's logistics operations. The analysis would have benefited from using primary data on Amazon's actual energy consumption. The feasibility of renewable energy projects could be better assessed by using site-specific technical parameters and consideration of other resource requirements such as cost of labour and power grid limitations.

This pre-feasibility analysis has shown that the renewable projects required to power Amazon's operations is very likely achievable, therefore further studies would be recommended to confirm the actual energy required by Amazon operations and the requirements for fulfilling the renewable energy project of choice.

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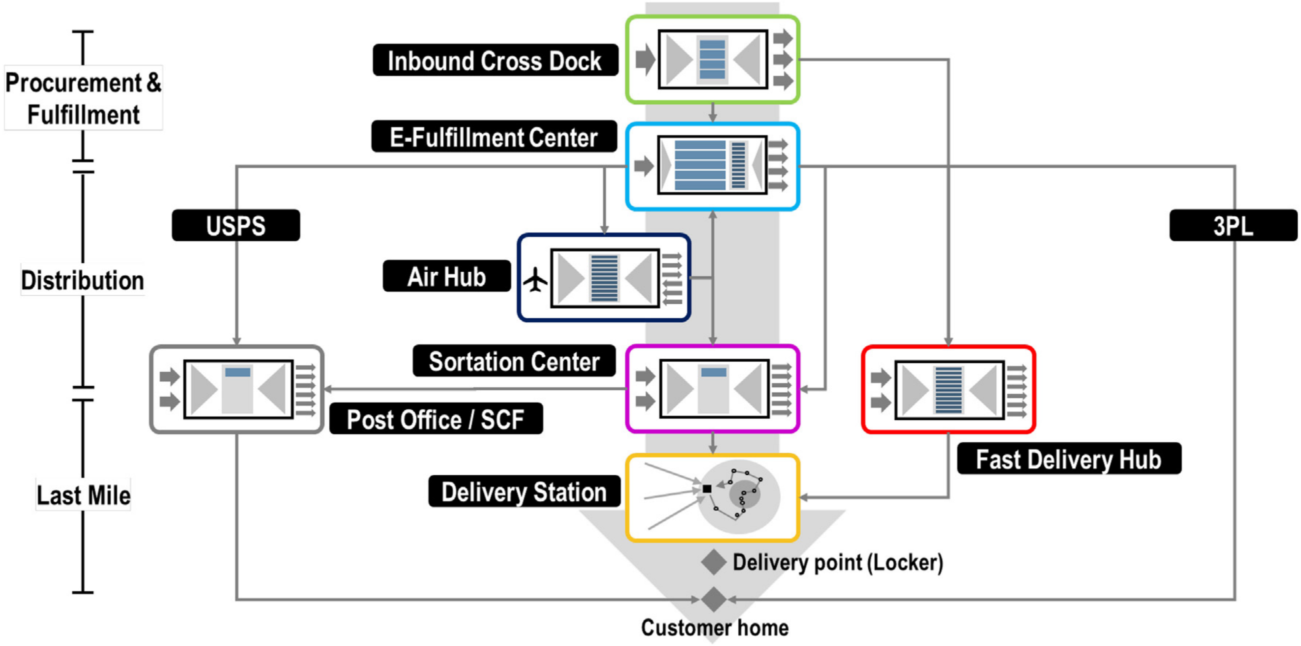
Appendices

Appendix 1:



The E-Commerce Supply Chain of Amazon (Rodrigue, 2020)

Appendix 2:

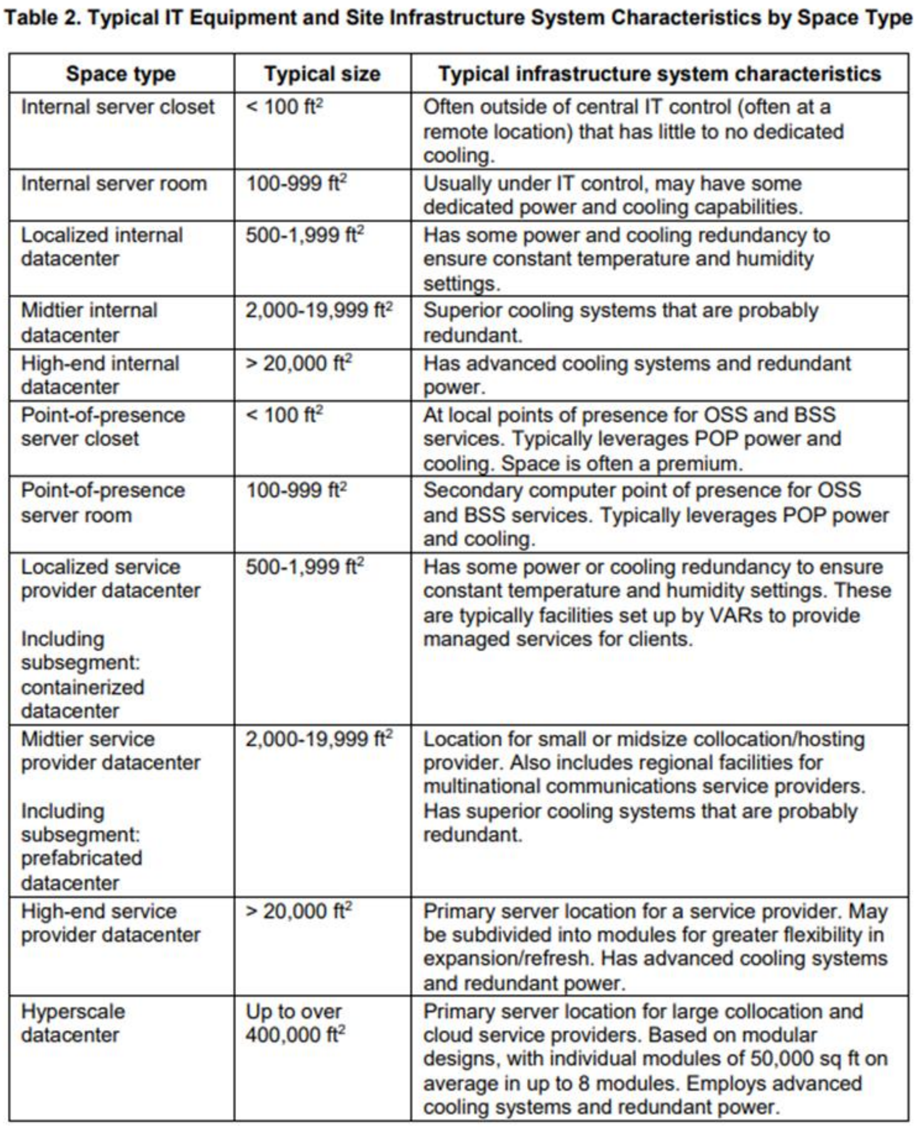
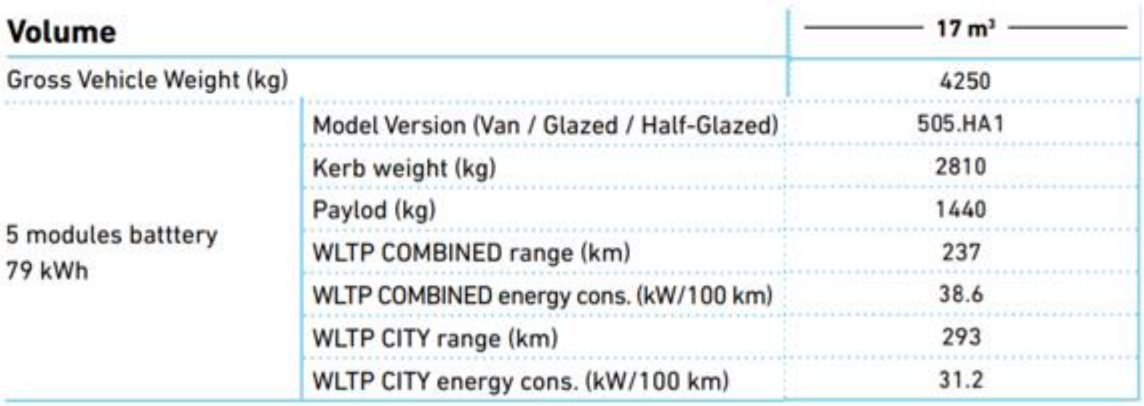


Table 2. Typical IT Equipment and Site Infrastructure System Characteristics by Space Type

Space type	Typical size	Typical infrastructure system characteristics
Internal server closet	< 100 ft²	Often outside of central IT control (often at a remote location) that has little to no dedicated cooling.
Internal server room	100-999 ft²	Usually under IT control, may have some dedicated power and cooling capabilities.
Localized internal datacenter	500-1,999 ft²	Has some power and cooling redundancy to ensure constant temperature and humidity settings.
Midtier internal datacenter	2,000-19,999 ft²	Superior cooling systems that are probably redundant.
High-end internal datacenter	> 20,000 ft²	Has advanced cooling systems and redundant power.
Point-of-presence server closet	< 100 ft²	At local points of presence for OSS and BSS services. Typically leverages POP power and cooling. Space is often a premium.
Point-of-presence server room	100-999 ft²	Secondary computer point of presence for OSS and BSS services. Typically leverages POP power and cooling.
Localized service provider datacenter Including subsegment: containerized datacenter	500-1,999 ft²	Has some power or cooling redundancy to ensure constant temperature and humidity settings. These are typically facilities set up by VARs to provide managed services for clients.
Midtier service provider datacenter Including subsegment: prefabricated datacenter	2,000-19,999 ft²	Location for small or midsize collocation/hosting provider. Also includes regional facilities for multinational communications service providers. Has superior cooling systems that are probably redundant.
High-end service provider datacenter	> 20,000 ft²	Primary server location for a service provider. May be subdivided into modules for greater flexibility in expansion/refresh. Has advanced cooling systems and redundant power.
Hyperscale datacenter	Up to over 400,000 ft²	Primary server location for large collocation and cloud service providers. Based on modular designs, with individual modules of 50,000 sq ft on average in up to 8 modules. Employs advanced cooling systems and redundant power.

Classification of Data Centre Types (Shehabi et al., 2016)

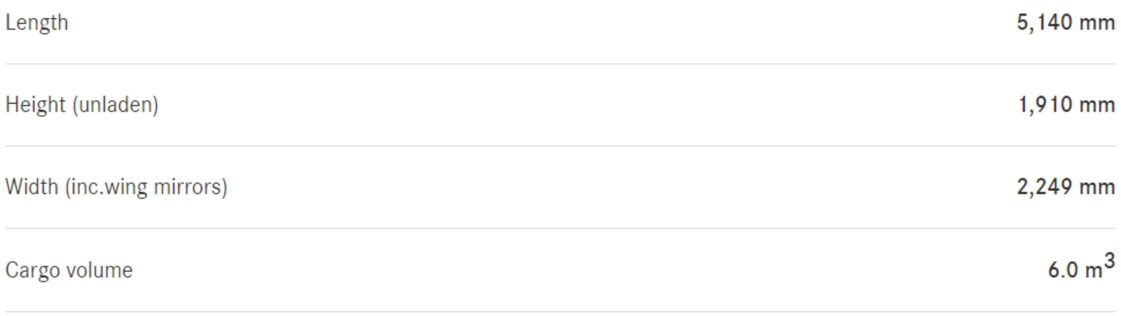
Appendix 3:



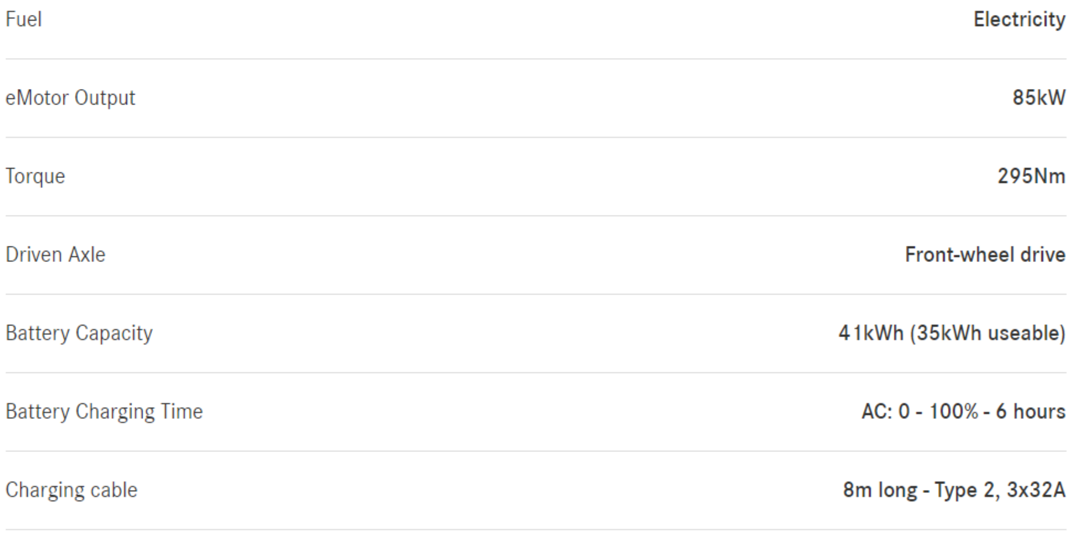
Volume		$17\ m^3$
Gross Vehicle Weight (kg)		4250
5 modules batttery 79 kWh	Model Version (Van / Glazed / Half-Glazed)	505.HA1
	Kerb weight (kg)	2810
	Paylod (kg)	1440
	WLTP COMBINED range (km)	237
	WLTP COMBINED energy cons. (kW/100 km)	38.6
	WLTP CITY range (km)	293
	WLTP CITY energy cons. (kW/100 km)	31.2

Reference Vehicle Technical Specifications (Fiat e-Ducato, n.d.)

Appendix 4:



Length	5,140 mm
Height (unladen)	1,910 mm
Width (inc.wing mirrors)	2,249 mm
Cargo volume	6.0 m^3

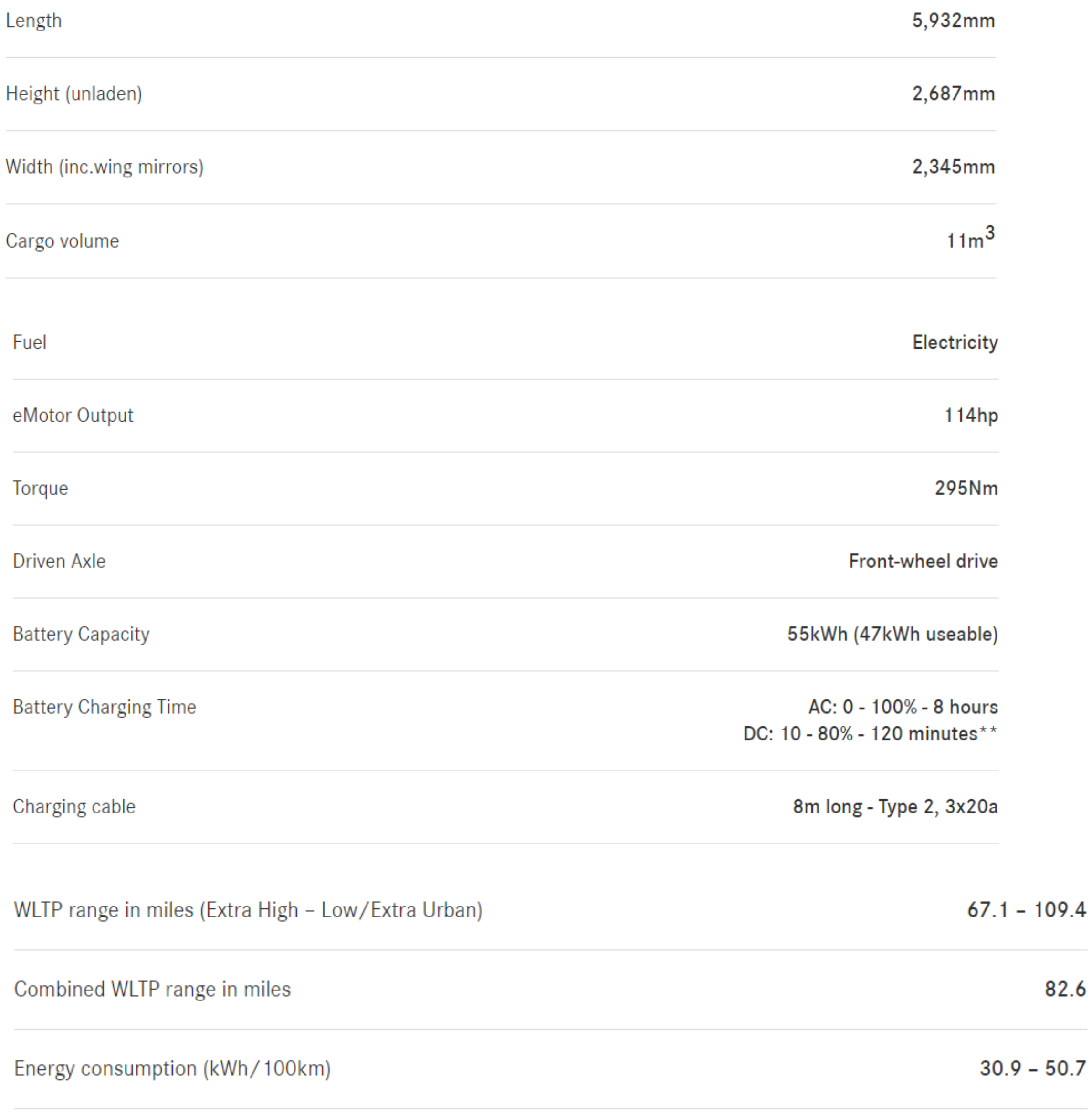


Fuel	Electricity
eMotor Output	85kW
Torque	295Nm
Driven Axle	Front-wheel drive
Battery Capacity	41kWh (35kWh useable)
Battery Charging Time	AC: 0 - 100% - 6 hours
Charging cable	8m long - Type 2, 3x32A

WLTP range in miles (Extra High – Low/Extra Urban)	81 - 103
Combined WLTP range in miles	92
Energy consumption (kWh/100km)	24.4 – 30.2
Speed limiter	75 mph

Mercedes-Benz e-Vito Technical Specifications (eVito Electric Panel Van Specifications, n.d.)

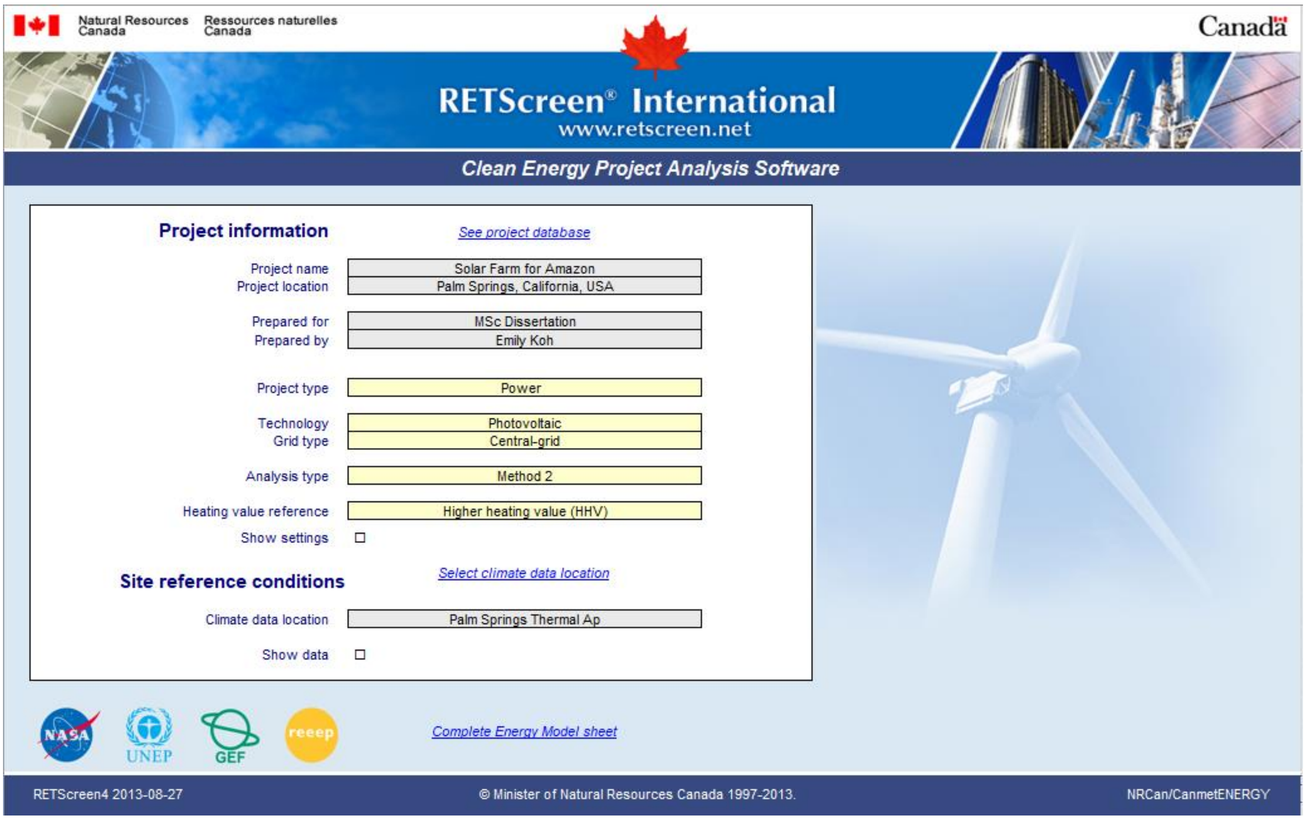
Appendix 5:



Length	5,932mm
Height (unladen)	2,687mm
Width (inc.wing mirrors)	2,345mm
Cargo volume	11m^3
Fuel	Electricity
eMotor Output	114hp
Torque	295Nm
Driven Axle	Front-wheel drive
Battery Capacity	55kWh (47kWh useable)
Battery Charging Time	AC: 0 - 100% - 8 hours DC: 10 - 80% - 120 minutes**
Charging cable	8m long - Type 2, 3x20a
WLTP range in miles (Extra High – Low/Extra Urban)	67.1 – 109.4
Combined WLTP range in miles	82.6
Energy consumption (kWh/100km)	30.9 – 50.7

Mercedes-Benz e-Sprinter Technical Specifications (eSprinter Electric Panel Van specifications, n.d.)

Appendix 6: Solar PV project



Project information

See project database

Project name: Solar Farm for Amazon
Project location: Palm Springs, California, USA

Prepared for: MSc Dissertation
Prepared by: Emily Koh

Project type: Power

Technology: Photovoltaic
Grid type: Central-grid

Analysis type: Method 2

Heating value reference: Higher heating value (HHV)

Show settings ☐

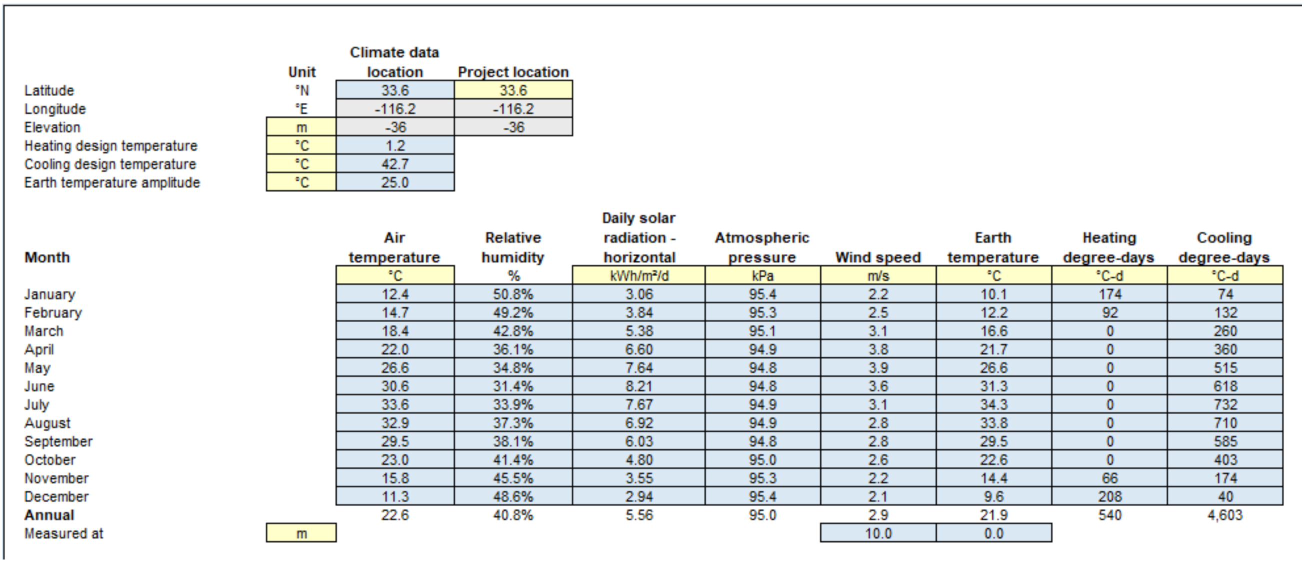
Site reference conditions

Select climate data location

Climate data location: Palm Springs Thermal Ap

Show data ☐

Complete Energy Model sheet



	Unit	Climate data location	Project location
Latitude	°N	33.6	33.6
Longitude	°E	-116.2	-116.2
Elevation	m	-36	-36
Heating design temperature	°C	1.2	
Cooling design temperature	°C	42.7	
Earth temperature amplitude	°C	25.0	

Month		Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
		°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January		12.4	50.8%	3.06	95.4	2.2	10.1	174	74
February		14.7	49.2%	3.84	95.3	2.5	12.2	92	132
March		18.4	42.8%	5.38	95.1	3.1	16.6	0	260
April		22.0	36.1%	6.60	94.9	3.8	21.7	0	360
May		26.6	34.8%	7.64	94.8	3.9	26.6	0	515
June		30.6	31.4%	8.21	94.8	3.6	31.3	0	618
July		33.6	33.9%	7.67	94.9	3.1	34.3	0	732
August		32.9	37.3%	6.92	94.9	2.8	33.8	0	710
September		29.5	38.1%	6.03	94.8	2.8	29.5	0	585
October		23.0	41.4%	4.80	95.0	2.6	22.6	0	403
November		15.8	45.5%	3.55	95.3	2.2	14.4	66	174
December		11.3	48.6%	2.94	95.4	2.1	9.6	208	40
Annual		22.6	40.8%	5.56	95.0	2.9	21.9	540	4,603
Measured at	m					10.0	0.0		

RETScreen Energy Model - Power project

Proposed case power system

Analysis type

○ Method 1
● Method 2

Resource assessment

Solar tracking mode		Azimuth
Slope	°	32.0

☑ Show data

Month	Daily solar radiation - horizontal kWh/m²/d	Daily solar radiation - tilted kWh/m²/d	Electricity export rate $/MWh	Electricity exported to grid MWh
January	3.06	5.12		2,488,727
February	3.84	5.69		2,470,157
March	5.38	7.54		3,532,428
April	6.60	8.44		3,763,895
May	7.64	9.72		4,385,999
June	8.21	10.31		4,419,380
July	7.67	9.60		4,208,303
August	6.92	9.00		3,951,669
September	6.03	8.21		3,532,600
October	4.80	7.39		3,387,586
November	3.55	5.92		2,728,559
December	2.94	5.18		2,530,841
Annual	**5.56**	**7.69**	**0.00**	**41,400,143**

Annual solar radiation - horizontal	MWh/m²	2.03
Annual solar radiation - tilted	MWh/m²	2.81

Photovoltaic

Type		mono-Si	
Power capacity	kW	18,327,359.59	
Manufacturer		Sunpower	
Model		mono-Si - SPR-320E-WHT	57273000 unit(s)
Efficiency	%	19.6%	
Nominal operating cell temperature	°C	45	
Temperature coefficient	% / °C	0.40%	
Solar collector area	m²	93,411,619	
Miscellaneous losses	%	5.0%	

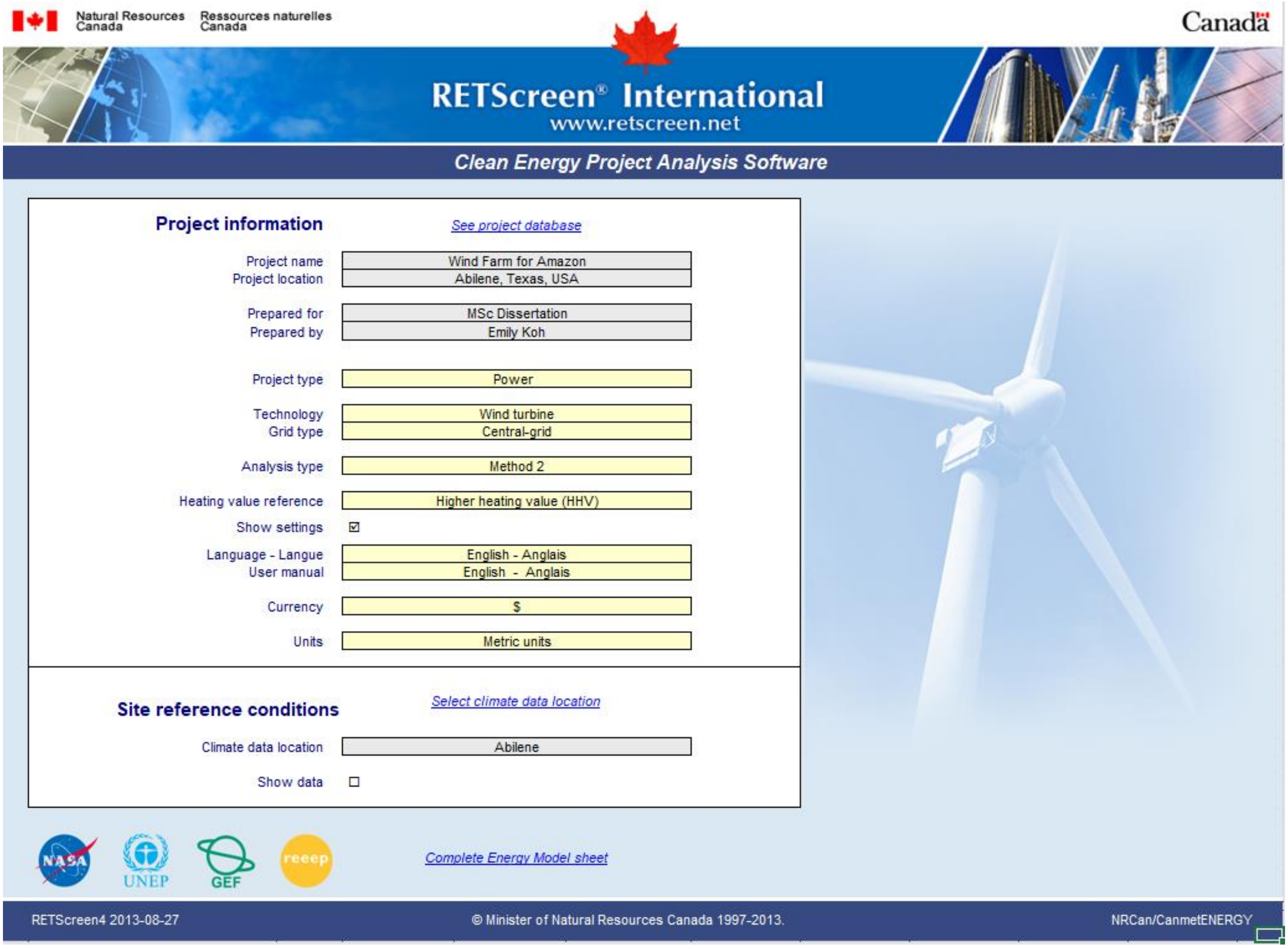
Inverter

Efficiency	%	98.0%
Capacity	kW	15999999.6
Miscellaneous losses	%	5.0%

Summary

Capacity factor	%	25.8%
Electricity exported to grid	MWh	41,400,143

Appendix 7: Onshore Wind project



Project information

See project database

Project name	Wind Farm for Amazon
Project location	Abilene, Texas, USA
Prepared for	MSc Dissertation
Prepared by	Emily Koh
Project type	Power
Technology	Wind turbine
Grid type	Central-grid
Analysis type	Method 2
Heating value reference	Higher heating value (HHV)
Show settings	☑
Language - Langue	English - Anglais
User manual	English - Anglais
Currency	$
Units	Metric units

Site reference conditions

Select climate data location

Climate data location	Abilene
Show data	☐

Complete Energy Model sheet

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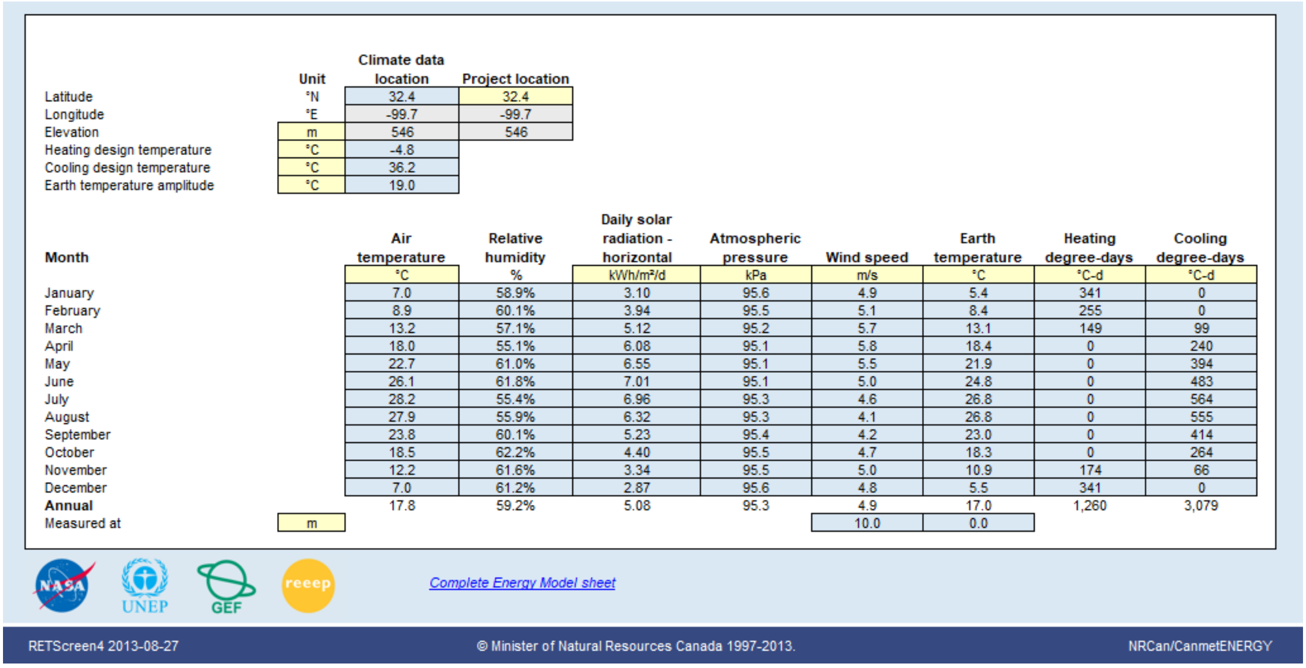

	Unit	Climate data location	Project location
Latitude	°N	32.4	32.4
Longitude	°E	-99.7	-99.7
Elevation	m	546	546
Heating design temperature	°C	-4.8	
Cooling design temperature	°C	36.2	
Earth temperature amplitude	°C	19.0	

Month		Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
		°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January		7.0	58.9%	3.10	95.6	4.9	5.4	341	0
February		8.9	60.1%	3.94	95.5	5.1	8.4	255	0
March		13.2	57.1%	5.12	95.2	5.7	13.1	149	99
April		18.0	55.1%	6.08	95.1	5.8	18.4	0	240
May		22.7	61.0%	6.55	95.1	5.5	21.9	0	394
June		26.1	61.8%	7.01	95.1	5.0	24.8	0	483
July		28.2	55.4%	6.96	95.3	4.6	26.8	0	564
August		27.9	55.9%	6.32	95.3	4.1	26.8	0	555
September		23.8	60.1%	5.23	95.4	4.2	23.0	0	414
October		18.5	62.2%	4.40	95.5	4.7	18.3	0	264
November		12.2	61.6%	3.34	95.5	5.0	10.9	174	66
December		7.0	61.2%	2.87	95.6	4.8	5.5	341	0
Annual		17.8	59.2%	5.08	95.3	4.9	17.0	1,260	3,079
Measured at	m					10.0	0.0		

Complete Energy Model sheet

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RETScreen Energy Model - Power project

Proposed case power system

Analysis type	○ Method 1 ○ Method 2 ● Method 3

Resource assessment

☑ Show data

Resource method

Month	Wind speed m/s	Abilene m/s	Electricity export rate $/MWh	Electricity exported to grid MWh
January	4.9	4.9		3,414,848
February	5.1	5.1		3,281,846
March	5.7	5.7		4,245,389
April	5.8	5.8		4,143,095
May	5.5	5.5		3,886,991
June	5.0	5.0		3,190,033
July	4.6	4.6		2,818,375
August	4.1	4.1		2,231,690
September	4.2	4.2		2,306,534
October	4.7	4.7		3,036,156
November	5.0	5.0		3,358,518
December	4.8	4.8		3,288,614
Annual	**4.9**	**4.9**	**0.0**	**39,202,090**

Measured at	m	10.0	10.0
Wind shear exponent		0.21	

Wind turbine

Power capacity per turbine	kW	3,000.0	
Manufacturer		Vestas	
Model		VESTAS V90-3.0 MW - 80m	
Number of turbines		5762	
Power capacity	kW	17,286,000.0	
Hub height	m	80.0	7.7 m/s
Rotor diameter per turbine	m	90	
Swept area per turbine	m²	6,362	
Energy curve data		Standard	
Shape factor		2.0	

Wind speed m/s	Power curve data kW	Energy curve data MWh
0	0.0	
1	0.0	
2	0.0	
3	0.0	708.0
4	106.0	1,858.2
5	243.0	3,515.1
6	417.0	5,525.1
7	640.0	7,670.5
8	940.0	9,765.6
9	1,285.0	11,695.9
10	1,659.0	13,404.6
11	2,052.0	14,865.4
12	2,447.0	16,065.9
13	2,736.0	17,003.0
14	2,923.0	17,683.6
15	3,000.0	18,124.0
16	3,000.0	
17	3,000.0	
18	3,000.0	
19	3,000.0	
20	3,000.0	
21	3,000.0	
22	3,000.0	
23	3,000.0	
24	3,000.0	
25 - 30	3,000.0	

☐ Show data

Array losses	%	15.0%
Airfoil losses	%	1.0%
Miscellaneous losses	%	2.0%
Availability	%	98.0%

Summary

Capacity factor	%	25.9%
Electricity exported to grid	MWh	39,202,090