Report on the climate impact of Known Mysteries & Solar Server, by Dr Benjamin Abraham *AfterClimate*

KNOWN MYSTERIES

Impact of developing KM:
650 to 690 kgCO2e for the whole project – less than one ton. Compared to Saltsea Chronicles: 47 tCO2e.

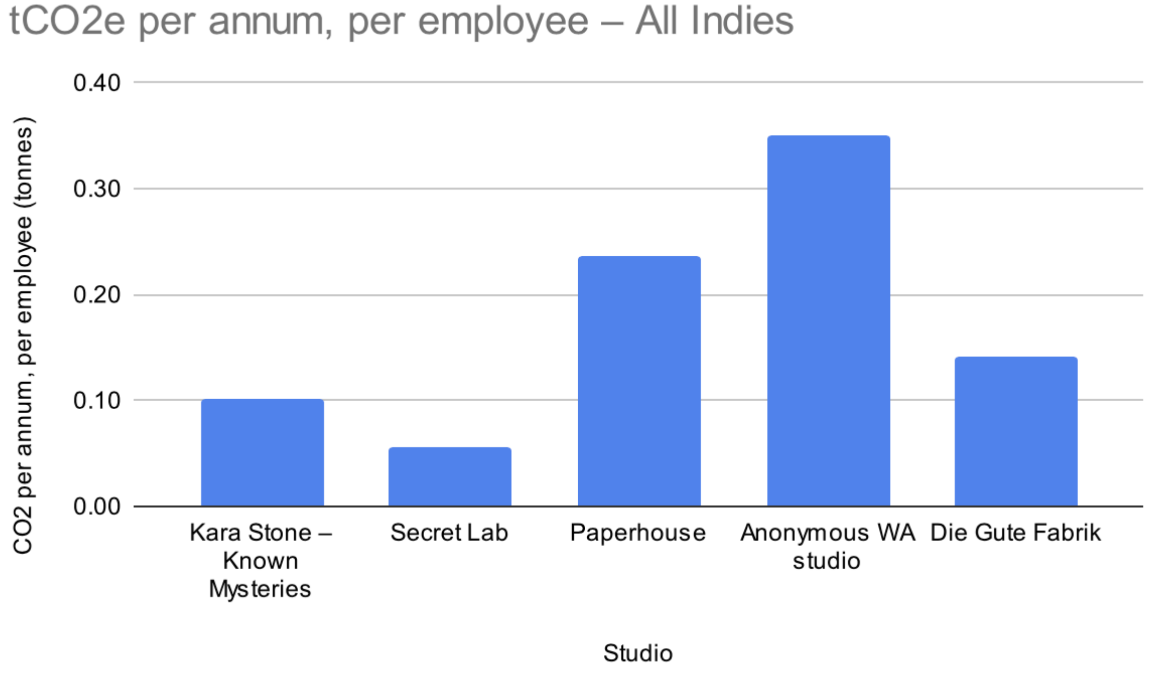
Largest source:
Travel – 460kg (70% of total footprint) from just one return trip YYC>SFO (3,270 km).

In summary: KM is about as low impact as any primarily solo developed game, in same range as other indie game productions, and with negligible impact in the context of the global game industry which emits ***tens of millions of tons of CO2*** per annum.

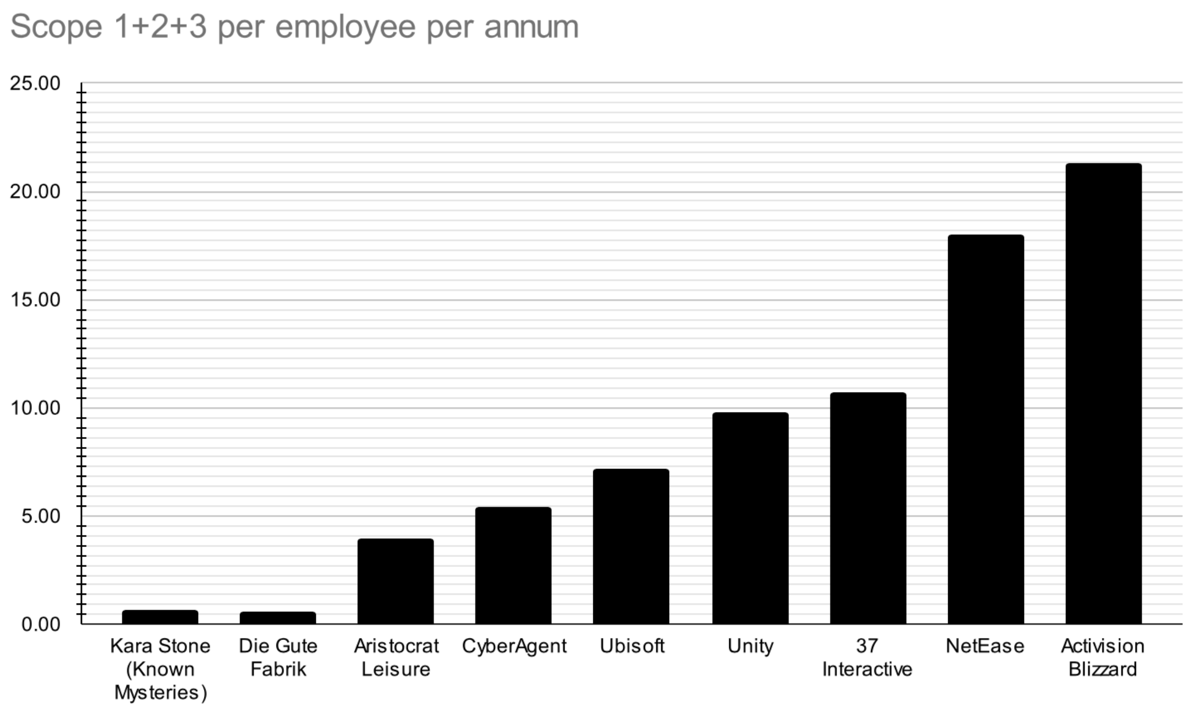
What could be improved: avoiding air travel if possible – e.g. by switching to remote presentation, travel via rail, and for distances (typically) under ~1000 km travel by car (even an individual, depending on fuel efficiency & other factors). Not always possible or practical in North America, or given time and other constraints.

Benchmarking against other indie productions / studios:

(Scope 1 & 2 emissions)



Even on a per-employee basis – a metric which should remain comparable regardless of business size – Known Mysteries is *tiny*, and nearly identical to DGF's per employee footprint.



SOLAR SERVER

To understand the impact of Solar Server, we have undertaken a number of scenarios to try and illuminate the dynamics involved in the creation and use of the server, with reference to an ordinary or "benchmark" alternative. An added complexity, however, is that because Known Mysteries was designed from the ground up as a low-energy game, a straightforward comparison to running the same game on a typical cloud server may be somewhat misleading, as it is likely to reflect as much (or more!) on *software* design choices than on the beneficial impact of running a game from Solar Server specifically.

There is no simple way around this issue, and would require creating complicated counterfactuals about what the game *would have been* had it been something completely different. This doesn't seem to make a lot of sense, so instead we have undertaken estimates to consider the climate impact of Solar Server and a benchmark system from three different angles: the first is from the perspective of embedded carbon (i.e. the CO2e emitted to manufacture the components of each system), the second is a calculation based on the estimated power consumption of both systems for one year, and the third is a calculation based on the average CO2e intensity of 1 GB of internet data transferred.

For our comparison, we have chosen an entry-level Microsoft Azure Virtual Machine as our benchmark – an Azure "Dv3 VM" which is advertised as running on a 2.3 GHz Intel XEON E5-2673 v4 (Broadwell). While this machine is more than sufficient for the demands of hosting Known Mysteries (which is designed for a low computing power environment, as mentioned) it was chosen as a relatively realistic alternative which is at least somewhat representative of a more capable and powerful system which might be used by a more traditional (i.e. non low-power) game. It is *also* a relatively "climate friendly" cloud solution, with Azure advertising that a high percentage of their energy needs come from renewables. With that caveat in mind, choosing a data centre located in regions with more fossil fuel power generation may produce higher emissions (as we will see in Scenario 2 on when we compare two different Azure regions, as well as an imaginary data centre in the state of Alberta, with a substantial range of impact).

Scenario 1: Embedded CO2 in Solar Server & Azure Dv3 VM

To illustrate the Solar Server system, a list of components was obtained, and a diagram of the system was created. Side by side with this diagram, a "traditional cloud scenario" was completed and the common components of the two systems identified. In the diagram (seen below), elements on one side or the other of the scenario illustrate the different components specific to each, with elements common between the two positioned across the centre line of the diagram. These shared components were left outside the system boundaries considered by the three scenarios – for example, taking Kara's 2017 MacBook Pro, the embedded carbon in which (approx 345 kg according to Apple product disclosures) is excluded from consideration given its equal presence in both systems.

For professional Life Cycle Analysis experts with access to paid databases like Ecoinvent and LCA software to build models of emissions, calculations of embedded carbon are (at least somewhat) straightforward. For the rest of us, we end up having to rely on manufacturers' disclosures, estimates based on similar products with known emissions, or at worst, on calculations derived from public input-output spend-based databases like USEEIO or EXIOBASE. (See [Die Gute Fabrik Climate Report] for more details on this process)

A search of existing manufacturer disclosures and other calculations of emissions from the literature was conducted for each main component. Embedded emissions for several components of the Solar Server were unable to be identified, so instead a rough two-order of magnitude range was used in their stead (10s to 100s of kg of CO2e) based on what might be plausible (leaning towards overestimation) based on the cost of the items, rough estimates from spend-based calculations, and previous experience.

The components of the solar server and their embedded emissions were: 150 watt solar panel (312 kg CO2e, based on Guo et al (2018)), PowMR 60A MPPT controller (14.62 kg CO2e, based on an EF from Climatiq database), Marine grade deep cycle sealed lead acid battery (10s - 100s kg CO2e, estimated range), Raspberry Pi 4B (U3C10) (10s - 100s kg CO2e, estimated range), 32GB flash card (10s - 100s kgs CO2e, estimated range). Adding those up, the total embedded carbon in the Solar Server system is estimated to be at least 326.62 kg CO2e plus 10s to 100s more, for **a likely total under 1 tonne of CO2e**.

Additionally, some of the main components of the solar server – including the solar panel, and the lead-acid battery – were obtained second hand, which further reduces the embedded footprint attributable to the project. Without knowledge of the age, previous use patterns, and several other details of these items we cannot say with real certainty what effects this might have on the amount counted against Solar Server. We can, however, be *almost* certain in saying that – from a planetary perspective – second hand purchases are nearly always preferable to brand new items where possible.

In comparison, according to an LCA study of a Dell PowerEdge R740 server blade (capable of running the specific Intel Xeon E5–2673 the Azure cloud Dv3 VM utilises) manufacturing of the device and all its components is estimated to involve **at least 4 tonnes of CO_2e**. This is a reasonable representation of the possible hardware involved in our chosen cloud server.

A similar complicating factor for attribution exists for the cloud server as well. A server rack may have a lifespan of several years and may service several virtual servers at once, reducing the total amount of its footprint we attribute to this project. It may also be replaced early under warranty, run inefficiently in a poorly optimised data centre, and so on for a great many other 'unknowns'. Given the introduction of the particular Intel Xeon chip used in this server occurred in 2016 and appears to still be in use according to Azure's VM listing page (as at 25/1/24), a 7 year lifespan for this device is not out of the question, and even a (generous) estimate by the cloud host for this project at 50% utilisation over one year would see an attribution figure for the total embedded emissions drop as low as 285 kg CO_2e – potentially well below the figure for our Solar Server estimate.

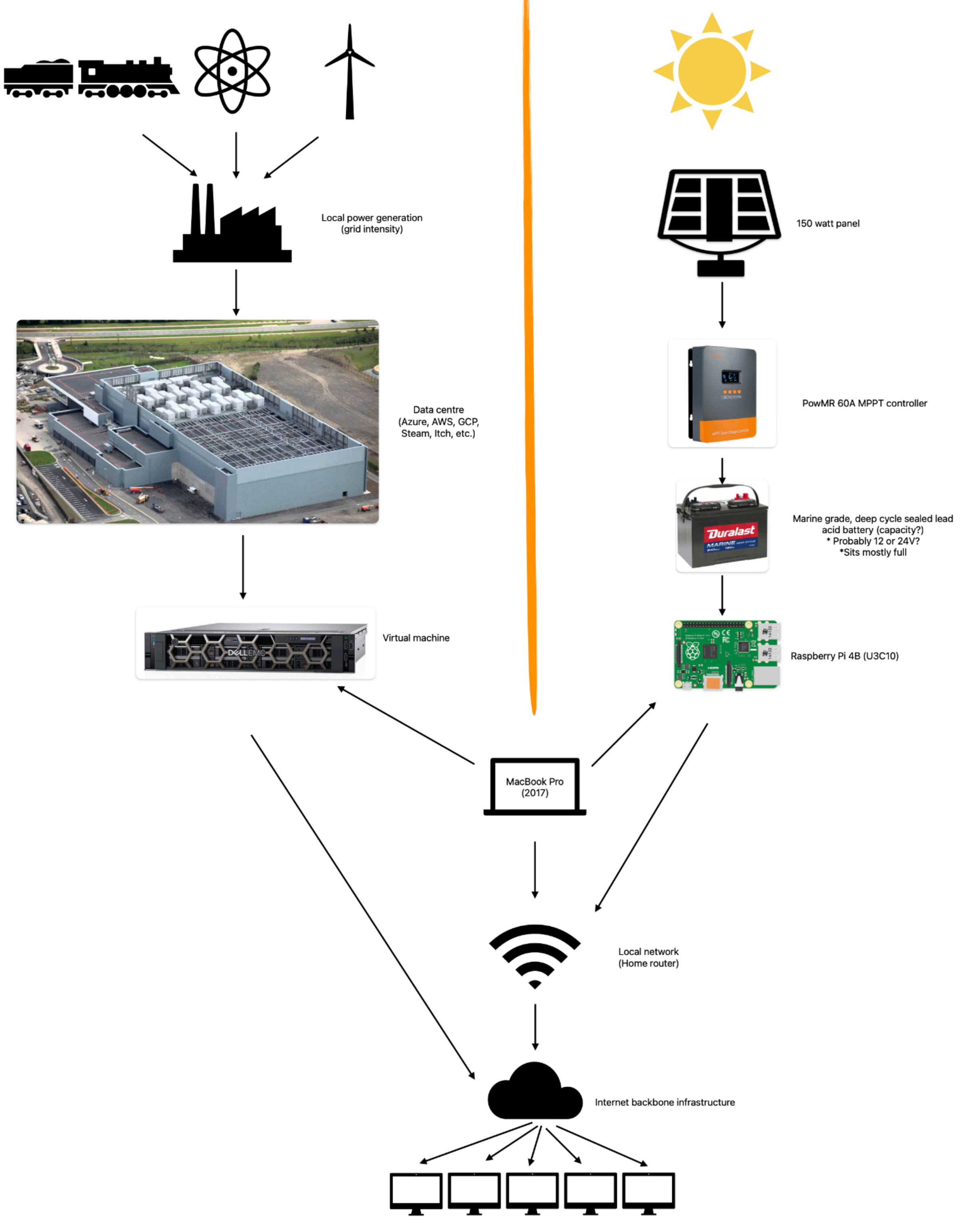
Given the uncertainties that remain in both our knowledge of the embedded costs of Solar Server and of the Azure VM it is extremely difficult to draw any definitive conclusions from this scenario, however. It may be plausible that, given certain efficiencies of the use of cloud computing, their massive economies of scale, and so on, that the use of the *right kind* of virtual machine may have a lower impact (in terms of embedded emissions) than a DIY solar server, depending on how responsibility for emissions are apportioned.

Responsibility for emissions from a data centre is "shared" in the sense that both the operator (e.g. Microsoft Azure, who may even contract out elements of the data centre to other third parties) and the user (e.g. Known Mysteries) both play a part in determining the footprint. The former, because choices made (like hardware fit-out, system design, and purchased renewable energy) make a major impact on system emissions. The latter, because the end user of the hardware has some degree of control over the design of the software, the utilization, etc.

Given these and other factors it is difficult to be entirely sure how to even approach, let alone be confident of achieving, a fair and reasonable balance in attribution. An underappreciated aspect of CO_2 impact measurement is the political nature of decisions of attribution, which become even more apparent when deciding "responsibility" for CO_2 between parties with such unequal power dynamics, such as a solo developer and one of the world's largest (trillion dollar) multinational businesses.

Traditional cloud scenario

Solar server scenario



Scenario 2: 1 year of operation of Solar Server & Azure Dv3 VM

The second scenario considers the annual energy consumption (and CO2e footprint) of the two servers. For Solar Server, a peak power use figure of 15 Watts is used, taken from the minimum specifications of the power supply required for the Raspberry Pi 4B. Once again, given that Known Mysteries is designed to be a low power game, and the operation of the server consists largely in sending the games highly-compressed files to the user, this is likely an overestimate of actual power consumption, so a second figure of 60% of max power consumption was also considered. If Solar Server ran at full power 24/7 for an entire year, it would use **131.4 kWh** of electricity. A more realistic (though still probably high in reality) annual level of 60% power would consume **78.84 kWh** of electricity. Since the emissions factor for solar electricity is 0, the emissions from one year of Solar Sever are zero in both cases (though whether the server stays up 24/7 at those power levels is a different story).

The equivalent electricity used by the Azure Dv3 VM at full power is 150 Watts for the CPU alone (with motherboard, storage and ram all using perhaps more power – excluded from these calculations for simplicity), with a max annual total of **1,314 kWh**, or a more realistic 60% utilisation rate annual total of **788.14 kWh**. Now here is where things get interesting. Microsoft's Azure service has a number of data centres in a variety of locations, with impacts on latency but more importantly for our purposes with different expected impacts based on regional energy intensity.

There are to main Canadian regional data centres that a cloud alternative to Solar Server could locate in – the first in Vancouver, seemingly connected to the "West US" region, with alternative regions on the east coast, including "Central Canada" (Toronto) and "Canada East" (Quebec). Locating in an Azure data centre in Vancouver is expected to produce a maximum of **37.45 kg CO2e** per annum, with a more realistic expected impact of **22.47 kg CO2e** from a year of operation. Quebec, however, is famous for getting almost all of its energy needs from hydroelectric power, with an expected maximum carbon footprint of just **1.7 kg CO2e** for the higher figure, and **1.02 kg CO2e** for the lower.

We can also consider a third (entirely hypothetical) Azure data centre located in Kara's home state of Alberta – which has a far higher grid supplied electricity emissions factor (0.7538 g CO2e/kWh vs Quebec's 0.0013 g CO2e/kWh). If the Azure server was located in Alberta instead of Quebec, and drew power from the ordinary power grid (aka, without a specific Power-Purchase Agreement) then the two energy consumption figures would attract annual carbon emissions figures closer to **990.5 kg CO2e** (max) or **594.3 kg CO2e** (60% load) for the higher and lower figures respectively. This highlights the importance of data centre energy sourcing, transparency, and the potential power of choosing the "right" data centre from a climate perspective. The right choice of data centre could literally mean, even for a small scale game running on a single VM, as much as one-half to a full ton of CO2e per year.

Scenario 3: CO2 estimates for data transfer by player count

The final scenario draws upon data centre energy consumption estimates by the IEA, as well as research by Aslan et al. (2017) which evaluates a series of studies of the energy consumption of data transmission across the internet. The following diagram below illustrates the simplified structure of the Internet Network, as presented by Aslan et al. (2017: 787):

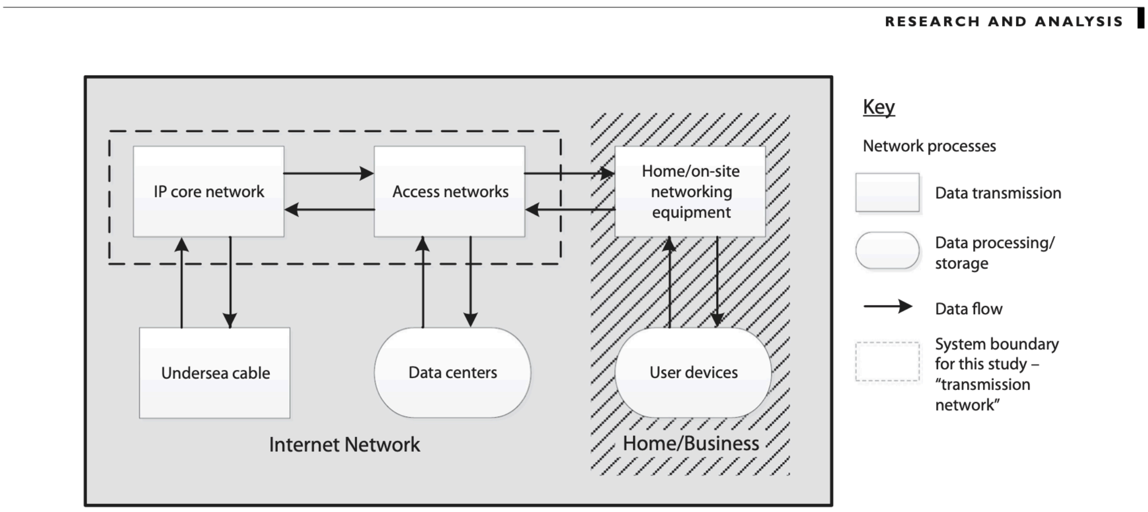
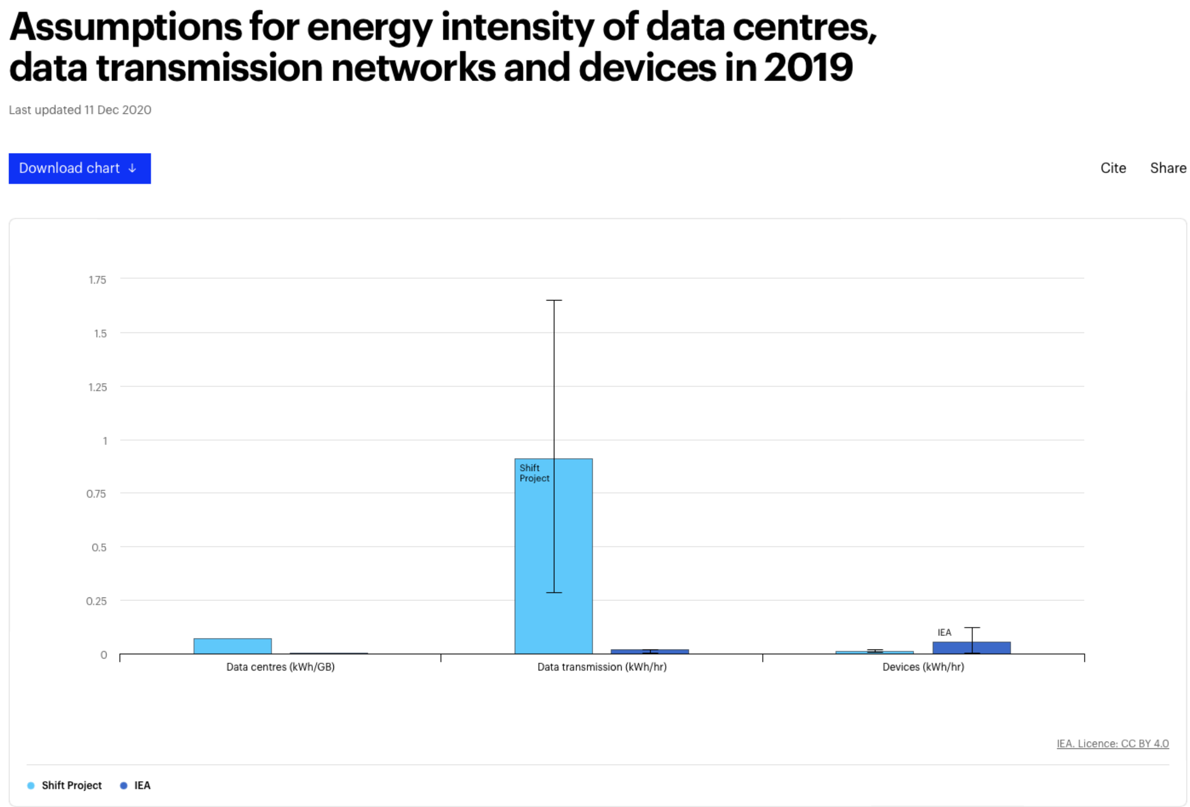


Figure 1 Simplified Internet structure diagram, showing scale over which key processes operate. The dotted box represents the common system boundary (for data transmission) selected for this study.

For our final scenario, the "system boundary" and "Home/Business" regions are essentially identical (or near enough) between both Solar Server and the Azure server, relying on much the same core and access network infrastructure for both. Instead, we want to make some educated assumptions about the data centre portion of the network, in order to estimate what sort of energy may be consumed by a data centre per GB of data transfer, exclusive of the shared network infrastructure.

While it was not the goal of Aslan et al.'s (2017) work to produce an estimate for data centre energy intensity per GB of data transmitted, their tabulation of previous research showed a 3x to as much as 20x ratio of energy consumption per GB. Further, their research found that the energy intensity of transmission networks was roughly *halving* every 2 years. Extrapolating this to 2024 in this final scenario, we have assumed that the electricity used to transfer a GB of data is now 1/8th what it was in 2016 when Aslan's study was undertaken, and assumed that the ratio of transmission to data centre energy consumption has remained similar, leading us to a figure of 0.06 kWh per GB (which matches the figure chosen by Sundberg (2021) informed by the same sources). This figure also sits neatly within the upper end of assumptions from the International

Energy Agency in 2019, with an expected range of 0.002 kWh per GB up to 0.072 kWh per GB in data centres. In the spreadsheet we have included options to explore the effect of all three power consumption estimates using a drop-down item.



To establish the amount of data transferred, we need to know the size of the game, and how many players download it. Known Mysteries is a three act structure, with the approximate total file size of the three acts being ~520 MB, or 0.52 GB. For simplicity's sake, we are assuming that every player downloads the whole game. The table below shows the results of these calculations for three different possible player counts.

Players	**MB transferred**	**2024 D.C. estimated transfer consumption (kWh)**	**Emissions – Quebec (kg CO2e)**	**Emissions – Ontario (kg CO2e)**	**Emissions – Alberta (kg CO2e)**
1,000	520,000	11.7	0.01521	0.02964	0.783952
10,000	5,200,000	117	0.1521	0.2964	7.83952
100,000	52,000,000	1170	1.521	2.964	78.3952

As a result, we can see that the Quebec based Azure server produces the lowest CO2 impact for the data transfer, with Ontario the next best, but that our hypothetical Alberta based data centre with its higher grid electricity carbon intensity has a substantially higher footprint – around 800x larger than Quebec.

Solar Server is not a typical data centre or file hosting server, however, and when comparing for a similar amount of data uploaded, the main constraint is likely to be the typical upload speed of a residential internet connection. To estimate energy consumption we have taken two different upload speeds – a “slow” speed of 1.25 MB/sec, and a “fast” upload speed of 3.75 MB/sec. With an upload speed and total amount of data to be transferred, we can now estimate the energy potentially consumed by Solar Server in delivering Known Mysteries to players. The following two tables show the duration (in hours) and the power consumption (kWh) for both fast and slow upload speeds. A final column shows how much CO2 emissions are potentially “saved” by Solar Server being powered by solar panel and battery rather than via Alberta’s power grid.

Slow uploads (1.25 MB/sec)

Players	MB transferred	Ordinary upload duration (hours)	Power consumption, slow upload (kWh)	kg CO2e total SAVED VS GRID
1,000	520,000	115.56	1.73	1.31
10,000	5,200,000	1155.56	17.33	13.07
100,000	52,000,000	11555.56	173.33	130.66

Fast uploads (3.75 MB/sec)

Players	MB transferred	Better upload duration (hours)	Power consumption, faster upload (kWh)	kg CO2e total SAVED VS GRID
1,000.00	520,000	38.52	0.58	0.44
10,000.00	5,200,000	385.19	5.78	4.36
100,000.00	52,000,000	3851.85	57.78	43.55

In both cases, the amount of CO2e saved by Solar Server avoiding grid based electricity emissions is small for all but the most high player counts.

Conclusions

Given the complexity in all three of the above scenarios, and the amount of remaining unknowns, and uncertainties, it remains difficult to draw strong conclusions.

In the first scenario, data on embedded emissions is still far too hard to come by. When examined purely from a total embedded CO_2 perspective, Solar Server's equipment likely emitted ¼ or less of the emissions from a single Azure Dv3 VM. However after attribution, given the intensely optimised nature of data centre compute capacity this assessment may be reversed, with the data centre coming out ahead (with the proviso that attribution for Solar Server's 2nd hand parts is next to impossible).

In the second scenario, Solar Server's power source being emissions free places it ahead of the Azure VM in all cases, however when the data centre is also powered by nearly 100% renewable power, the significance of its lead narrows. In a (purely hypothetical) data centre of the same specification, located in the same state as Solar Server, running purely from grid supplied energy, the savings from 1 year of operation of Solar Server grows to approx 0.5-1 tonnes of CO_2e, a far more substantial amount avoided. This result is likely similar to the entire embedded CO_2 footprint of the Solar Server system, and if this were our main comparison, we would describe a "payback" period of Solar Server to be around 1 year. Beyond the first year, it starts preventing emissions (assuming no other changes). However, given the availability of data centres powered by a high percentage of renewables, it describes the effect of displacing grid consumption in a high carbon energy system.

The final scenario is the most speculative, based on inferences drawn from research into data transmission energy consumption. Here we estimated (acknowledging the great room for error) that the Solar Server may consume as little as 0.58 kWh in a year (with a fast upload speed and only 1000 players), and as much as 173.33 kWh in a year (with slow upload speed and 100k players). If these were replacing a grid-powered server of the same specifications in the same location, they would be displacing 0.44 kg CO_2e – 130.66 kg CO_2e respectively.

Similarly, the Azure data centre was estimated to use as little as 11.7kWh, or as much as 1,170 kWh in a year, with an emissions range of 0.015 kg CO_2e per year (in Quebec, with 1000 players), up to 881.946 kg CO_2e per year (in a hypothetical Alberta data centre, with 100k players).

Recommendations

Where, and to whom, can we recommend a Solar Server type system? The first is to anyone who, for whatever reason, cannot access or identify a suitable data centre or server host powered by a high percentage of renewables. Given that a great many cloud operators have net zero targets – Azure (by 2025), Google cloud (by 2030), and AWS (by 2040) included – and others have begun to advertise the environmental credentials of their cloud services, this seems likely to be a small (and potentially shrinking) group.

The second group we would recommend a Solar Server to is to anyone who wishes to design games for a different approach to energy intensity, and to explore the constraints and opportunities of low-power game design. Is it possible to do so while hosting a game on an Azure cloud server? Possibly, but without the direct interface with such a physically limited server system much of the hands-on potential seems likely to be lost.

Given the calculations and comparisons above, it is hard to recommend a Solar Server type arrangement to the ordinary game dev who simply wishes to reduce their climate impact. The time commitment, effort and potentially small CO_2e savings involved suggests time would be better spent by finding a suitable, 100% renewable powered data centre or hosting solution that meets their needs.

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