Thermo-Fluids:
Product Design Embodied Energy Assessment

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Concept Description

The 4s was significant in the world of smart phones, with its form being so recognisable with the 'boxy' edges, that you can still see elements of its design used in the iPhone 12 released this year. It was also the iPhone that took the longest to develop, and the last iPhone released before the death of Steve Jobs.

The embodied energy was broken down to two main categories. The production stage of the phone including material, production and transport, and the use phase including energy from charging, and data usage.

Through detailed analysis, some key embodied energy figures were discovered. It was found that the embodied energy in production was 229.8 MJ, transport was 26 MJ.

The majority of the materials embodied energy came from the Logic board as well as other multi-material components, rather than the pure materials such as stainless steel. 19 MJ of the transport energy was from trucks transporting the parts of the phone.

Use by a light user, 1 charge a day, and a heavy user was 22.63, 31.93 and 62.26 retrospectively. Data and WiFi usage over the product lifetime made up 1093 MJ which was a large and unexpected contributor to the embodied energy.

However, the figures were backed up by other articles and research that provided similar numbers.

Key Specs[1]

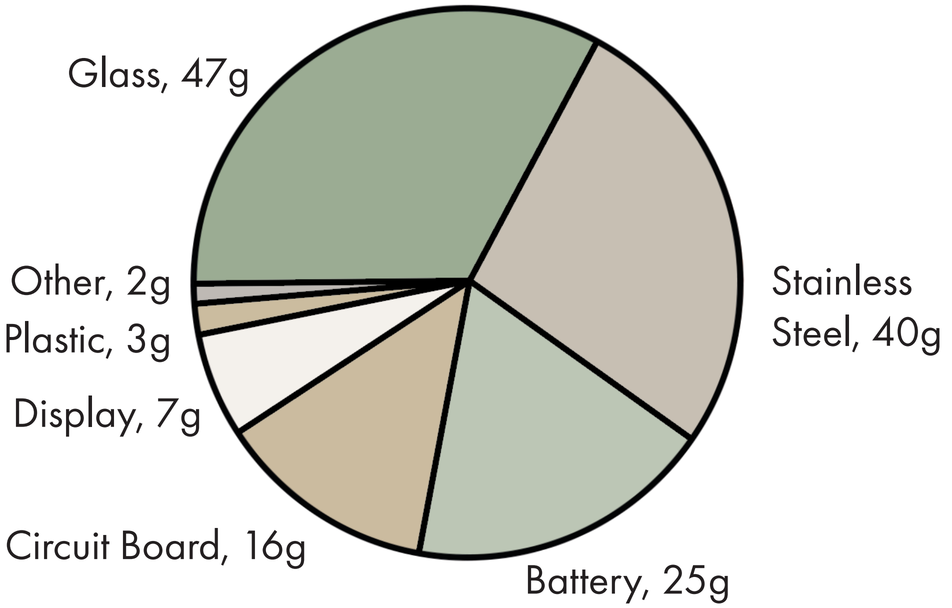
Brand - Apple	Size - 115.2*58.6*9.3 mm
Release Year - 2011	RAM - 512 MB
Mass - 140 g	Storage - 8, 32, 64 GB
Battery - 1432 mA h	Chipset - Apple A5
Price - From £500	Network gen - 3G

[1] https://www.gsmarena.com/apple_iphone_4s-4212.php

Materials

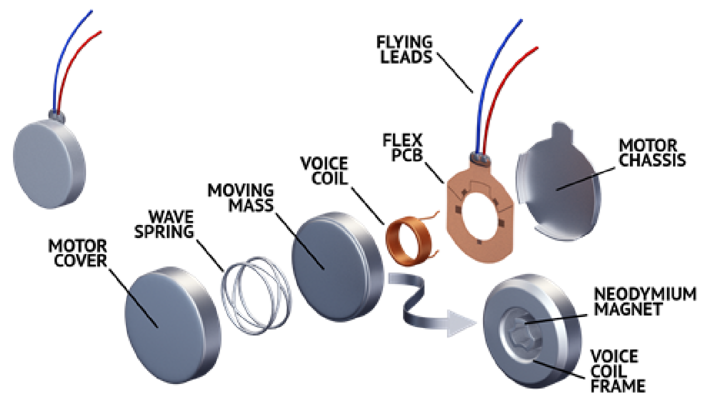
Material Breakdown

This is the mass of material in the 4S from Apple's official report[1]. This shows that most of the materials embodied energy can easily be found, apart from the 'other 2g' of material.

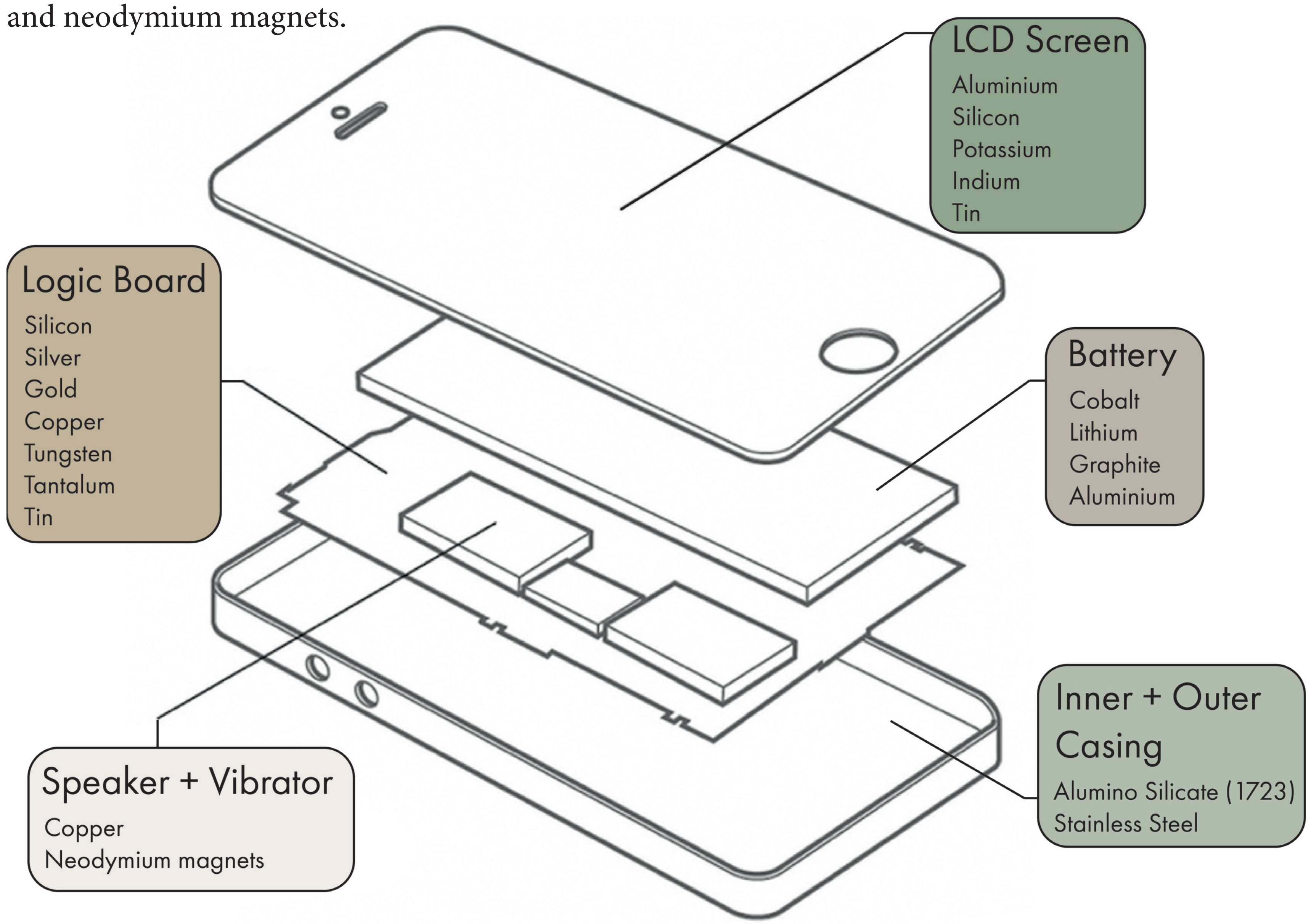


Speaker and Vibrator Materials

The vibrator is a linear resonant actuator[4] which is made mostly of copper and neodymium magnets. The composition can be seen in the diagram below, and they help the phone vibrate for alerts etc.

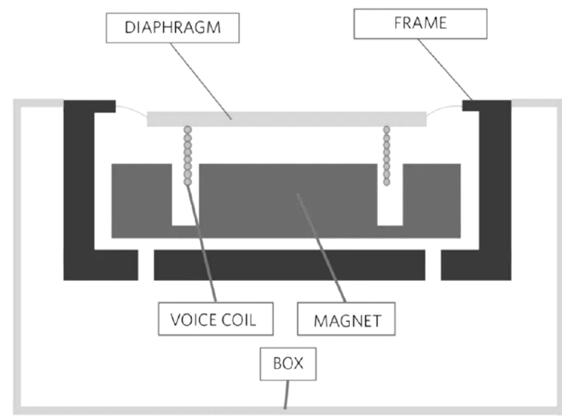


After looking at a source that breaks each component of the phone into individual materials[2], it could be visualised to see where different materials came from. However, two components were identified that didn't have their materials listed on the Apple report. These were the speaker and vibrator[3], containing copper and neodymium magnets.



The speaker is actually made of similar materials[5]. This is because it works with a combination of a voice coil and a magnet. This is again mostly copper and neodymium.

Therefore, for the other 2g of material, this can be split evenly as 1g neodymium and 1g of copper for both of theses products combined.



[1] https://www.apple.com/environment/reports/docs/iPhone4S_Product_Environmental_Report_2011.pdf
[2] https://www.visualcapitalist.com/extraordinary-raw-materials-iphone-6s/
[3] https://www.researchgate.net/publication/327440935_Characterizing_the_Materials_Composition_and_Recovery_Potential_from_Waste_Mobile_Phones_A_Comparative_Evaluation_of_Cellular_and_Smart_Phones
[4] https://www.precisionmicrodrives.com/vibration-motors/
[5] http://www.farnell.com/datasheets/2869785.pdf

Materials

Embodied Energy

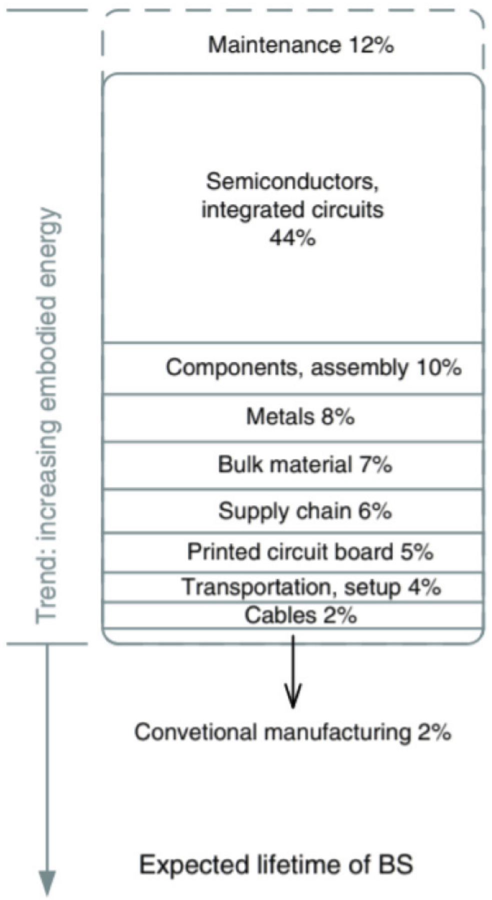
The materials embodied energy for kg can be found on Granta Edupack. Then with the masses known for the materials then total embodied energy can be calculated. For some components where the exact composition of materials wasn't known, the embodied energy per kg of the component was found, from which the embodied energy of the component can be found. The packaging, charger and earphones were not accounted for as they weren't actually part of the phone.

Material	Component	Mass (g)	Material Energy (MJ)	Processing Energy (MJ)	Total Energy (MJ)	Total CO2
Glass	Screen	47	0.73	0.52	1.25	0.048
Stainless Steel	Outer body Inner body	40	3.8	0.097	3.917	0.27
Cobalt	Battery	25	22	Inc	22	2.5
Aluminium						
Lithium						
Graphite						
Gold	Circuit (logic) Boards	16	200	Inc	200	11
Silver						
Copper						
Tungsten						
Tantalum						
Silicon						
Silicon Dioxide	Display	7	1.7	Inc	1.7	0.13
Liquid Crystal						
Indium tin oxide						
Plastic (ABS+PBT)	Inner Body	3	0.34	0.39	0.73	0.018
Copper	Coils	1	0.059	0.001	0.06	0.0039
Neodymium	Magnets	1	0.092	0.0081	0.1	0.0074
LED	LED	0.003	0.014	Inc	0.014	0.00069
Phone Total		**140**	**228.74**	**1.016**	**229.8**	**13.98**

Source: https://www.ansys.com/products/materials/granta-edupack

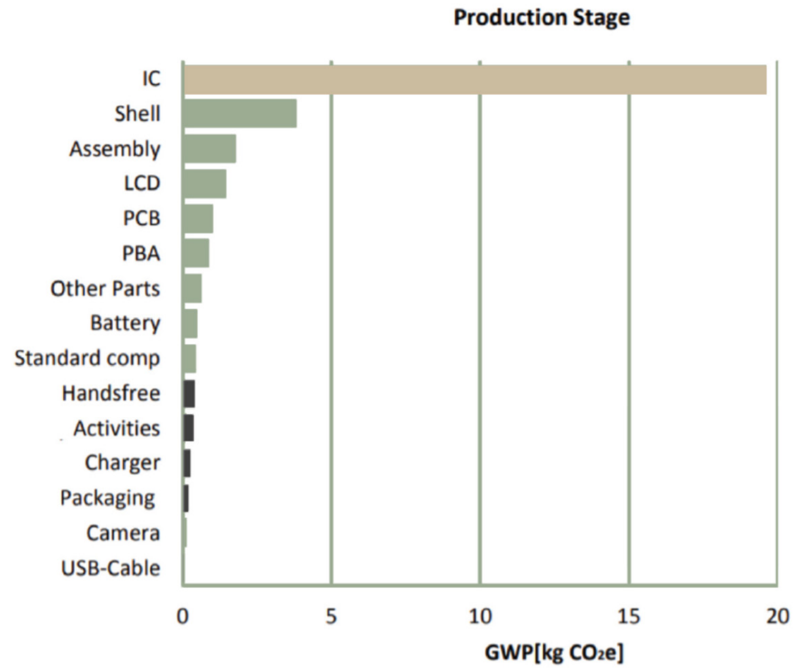
Logic Board Value

After finding the embodied energy values per kg of the components, it could be seen that the logic board has a disproportionately large value. Therefore this was investigated to ensure it was a reliable value.



From looking at two sources[1], it can be seen that the IC value is much higher than other values for energy and CO2.

Therefore my values are validated, and the total energy can be calculated.



[1] https://books-library.online/files/books-library.online-08061459Mk7J6.pdf

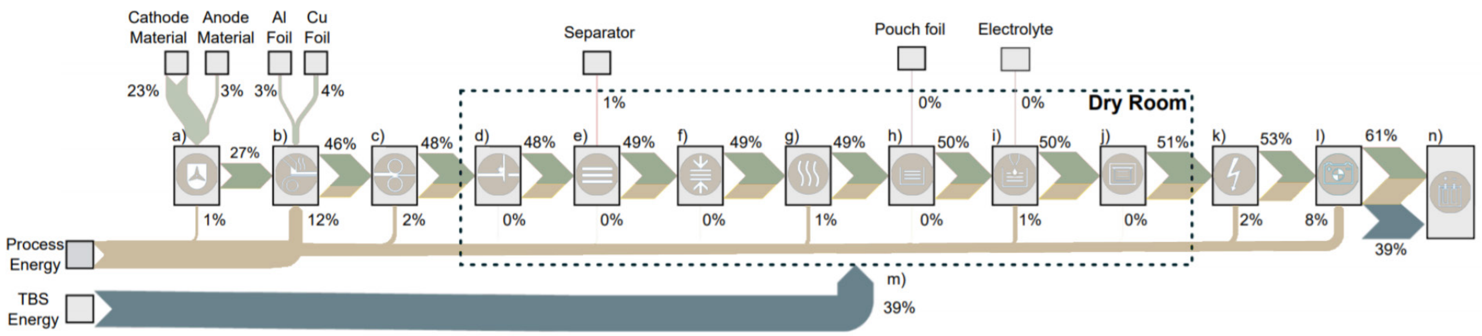
Calculations

Battery Embodied Energy

The battery has a complex production as seen in the table and diagram[1]. It has a high value of 1153.6[1] W h per 1 W h of battery capacity:

$$EE = Battery\ Capacity \times EE/Wh$$
$$= 5.3 \times 1153.6$$
$$= 6114.08\ Wh$$
$$= 22.01\ MJ$$

	Material Energy	Process Energy	Embodied Energy
a) Mixing	295.8	11.3	307.1
b) Coating/drying	79.0	142.3	528.4
c) Calendering		22.1	550.5
d) Separation		0.1	550.6
e) Packaging	9.6	1.3	561.5
f) Contacting		0.1	561.6
g) Final drying		6.4	568.0
h) Housing	3.8	0.6	572.4
i) Electrolyte filling & closing	2.8	9.2	584.4
j) Tempering		0.6	585.0
k) Formation		27.6	612.6
l) Aging		92.3	704.9
m) TBS		448.7	1153.6
n) Total	391.0	762.6	1153.6



Logic Board Embodied Energy

The logic board consists of 15 IC's and has a mass of 16g. The embodied energy from 'Materials and the Environment' [2] has a range between 9700-16000. If we take the average of this, we can find a value for the embodied energy.

$$\frac{9700 + 16000}{2} = 12850\ MJ/kg$$

$$12850 \times 0.016 = 205.6\ MJ \approx 200\ MJ$$

Other Materials Embodied Energy

The other materials embodied energy could be calculated with the energy values per kg. There are material embodied energy's and also manufacturing and these were calculated separately:

Stainless steel (Virgin, AISI 310) material, production and total embodied energy:

$$EE = Mass \times \frac{EE}{kg} = 0.04 \times 95 = 3.8\ MJ$$
$$= 0.04 \times 2.425 = 0.097\ MJ$$
$$3.8 + 0.097 \quad Total = 3.897\ MJ$$

Glass (Virgin, Alumino Silicate) material, production and total embodied energy:

$$EE = Mass \times \frac{EE}{kg} = 0.047 \times 18.25 = 0.73\ MJ$$
$$= 0.047 \times 13 = 0.52\ MJ$$
$$0.73 + 0.52 \quad Total = 1.25\ MJ$$

Plastic (Virgin, ABS+PBT) material, production and total embodied energy:

$$EE = Mass \times \frac{EE}{kg} = 0.003 \times 113.3 = 0.34\ MJ$$
$$= 0.003 \times 130 = 0.39\ MJ$$
$$0.34 + 0.39 \quad Total = 0.73\ MJ$$

Copper (Virgin, C10500) material, production and total embodied energy:

$$EE = Mass \times \frac{EE}{kg} = 0.001 \times 59 = 0.059\ MJ$$
$$= 0.001 \times 1 = 0.001\ MJ$$
$$0.059 + 0.001 \quad Total = 0.06\ MJ$$

Magnets (Virgin, Neodymium) material, production and total embodied energy:

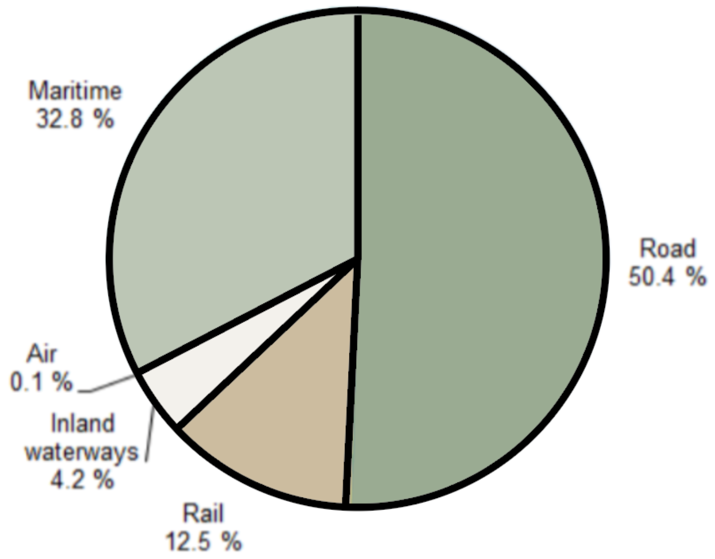
$$EE = Mass \times \frac{EE}{kg} = 0.001 \times 92 = 0.092\ MJ$$
$$= 0.001 \times 8.1 = 0.0081\ MJ$$
$$0.092 + 0.0081 \quad Total = 0.1\ MJ$$

[1] https://www.sciencedirect.com/science/article/pii/S2212827119301015
[2] https://www.elsevier.com/books/materials-and-the-environment/ashby/978-0-12-385971-6

Calculations

Transport Embodied Energy

As seen from the map figure of Apple's production of components (in tonnes) in 2011, you can see that their production is worldwide, and there will be significant energy used to transport material to these places, and then ship the components to a factory that assembles the final phone:

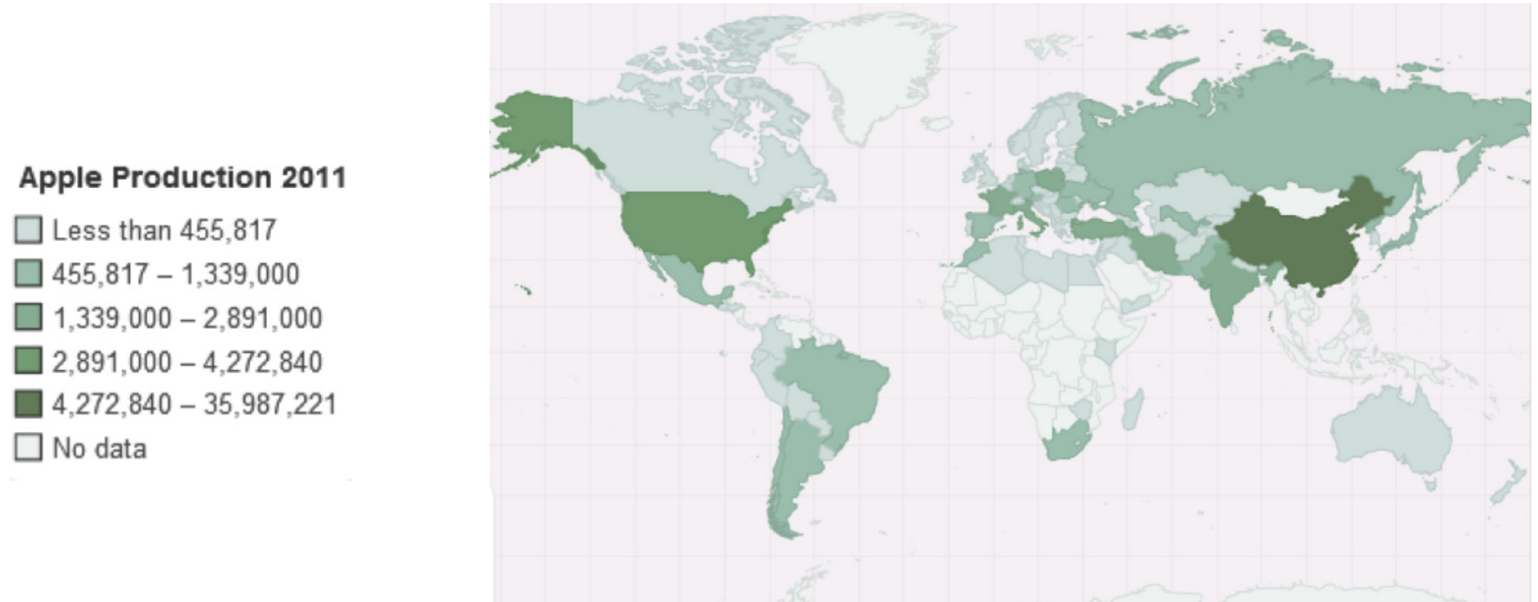


$$Total\ Distance \approx 240\,000\ miles \approx 386000\ km$$

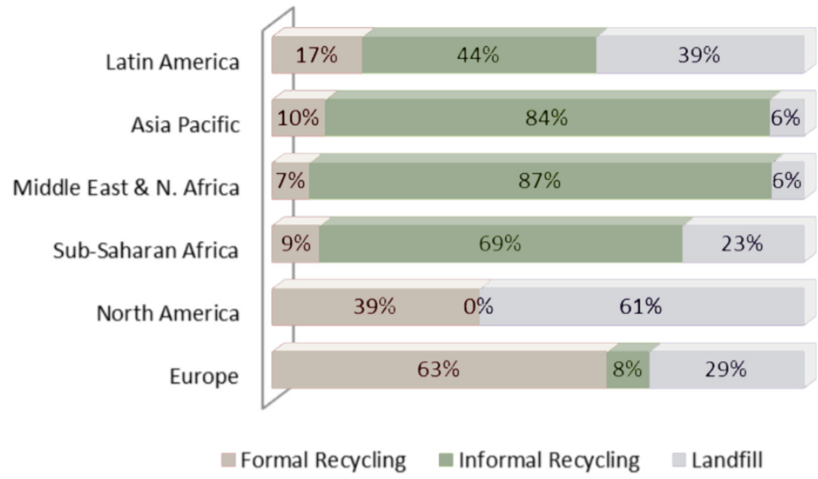
$$Distance\ Travelled = Total\ Distance \times Proportion\ of\ Total\ Travel\ by\ Freight\ Type$$

$$Distance\ (Truck) = 384\,600 \times 0.504 = 193838.4\ km$$
$$Distance\ (Maritime) = 384\,600 \times 0.328 = 126148.8\ km$$
$$Distance\ (Rail) = 384\,600 \times 0.125 = 48075\ km$$
$$Distance\ (Inland\ Waterway) = 384\,600 \times 0.042 = 16153.2\ km$$
$$Distance(Air) = 384600 \times 0.001 = 384.6\ km$$

These distances and the freight type were then put into Granta Edupack and by using the freight energy per kg of material, in the phones instance 140g, the total energy was found. This figure was 26 MJ and 1.9 kg of CO2 which is not far from the 6% transport value by Apple when compared to the 69% material value which equated to 13.98 kg.



End of life Embodied Energy Saving



When a phone comes to its end of use, there is a chance to reduce the embodied energy for future smart phones. Elements such as gold and silver can be recovered. However, the lithium ion battery can be focussed on as recycling them has 90% smaller ecological footprint than primary mining[5]. Therefore we can find the energy saved by recycling a battery, with embodied battery energy. The battery had an embodied energy of 22 MJ:

$$0.9 \times 22 = 19.8\ MJ\ saved\ per\ phone$$

However, this assumes all phones are recycled. From the graph above[6] a lot of phones go to landfill, but taking Europe as an example, 71% of smart phones are eventually recycled. Therefore we can find an average for the energy saved per phone battery using this 71% value:

$$19.8 \times 0.71 = 14.06\ MJ$$

If we find the percentage saving by looking at the original 22 MJ value, we can see the importance in terms of embodied energy of recycling smart phones.

$$\left(\frac{22-14.06}{22}\right) \times 100 = 36.1\%$$

Summary

Total embodied energy for the iPhone 4S was 229.8 MJ including materials and processing. Transport came to 26 MJ, and we saw a 36.1% saving could be made from recycling the phones lithium-ion battery. The material, production and transport total is extremely close to the 250 MJ figure provided by IEEE Spectrum[7].

[1]https://www.ertrac.org/uploads/documentsearch/id56/ERTRAC-Long-duty-Freight-Transport-Roadmap-2019.pdf
[2]https://www.wired.com/2016/04/iphones-500000-mile-journey-pocket/
[3] https://www.apple.com/environment/reports/docs/iPhone4S_Product_Environmental_Report_2011.pdf
[4]http://chartsbin.com/view/11627
[5] https://www.theguardian.com/sustainable-business/recycling-smartphone-batteries-vital-sustainability
[6] http://kth.diva-portal.org/smash/get/diva2:839633/FULLTEXT01.pdf
[7] https://spectrum.ieee.org/energy/environment/your-phone-costs-energyeven-before-you-turn-it-on

Calculations Use

For the usage of the phone, calculations including energy of the battery, energy of the charger, and energy of data were carried out.

Firstly, the power for heavy usage and light usage were found. Standby power[1] was found to be 0.03 W and usage current was 0.522 A[2]. Multiplying this by the battery voltage (3.8 V[3] the power was found.

$$Power = 0.03\ W$$

$$Power = IV$$
$$= 0.522 \times 3.8$$
$$= 1.98\ W$$

<u>Light use</u>

From this the light use energy for lifetime of the product could be calculated, with light usage time being 7%[4], lifetime being 2.5 years[5], and efficiency of the battery being 75%[6], and iPhone charger efficiency being 74%[7].

$$Usage\ Energy = \frac{T \times P}{Efficiency}$$

$$= \frac{T_S \times P_S + T_U \times P_U}{Efficiency}$$

$$= \frac{(0.93 \times 0.03) + (0.07 \times 1.98)}{0.75} = 0.213\ W$$

$$Lifetime\ Energy = P \times T$$
$$= 0.213 \times (2.5 \times 52 \times 7 \times 24 \times 60 \times 60)$$

$$= 16.75\ MJ$$

$$Charging\ Energy = \frac{Energy\ Consumed}{Charger\ Efficiency}$$

$$= \frac{16.75}{0.74} = 22.63\ MJ$$

<u>Heavy use</u>

For heavy use energy, the usage time is 21%[4]. with the same lifetime and efficiencies, the energy was calculated, and the much higher value can be seen.

$$= \frac{T_S \times P_S + T_U \times P_U}{Efficiency}$$

$$= \frac{(0.79 \times 0.03) + (0.21 \times 1.98)}{0.75} = 0.586\ W$$

$$= 0.586 \times (2.5 \times 52 \times 7 \times 24 \times 60 \times 60)$$

$$= 46.07\ MJ$$

$$Charging\ Energy = \frac{46.07}{0.74} = 62.26\ MJ$$

[1] https://www.electronicproducts.com/meeting-30-mw-standby-in-mobile-phone-chargers/#:~:text=Most%20current%20mobile%20phones%20current-ly,of%20150%20to%20300%20mW.&text=Although%20relatively%20simple%20to%20implement,capacity%20and%20improving%20service%20life.
[2] https://www.sciencedirect.com/science/article/pii/S1877050916317756
[3] https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Technology-Media-Telecommunications/gx-tmt-pred15-smartphone-batteries.pdf
[4] http://kth.diva-portal.org/smash/get/diva2:677729/FULLTEXT01.pdf
[5] https://www.coolblue.nl/en/advice/lifespan-smartphone.html
[6] https://dl.acm.org/doi/10.1145/2333660.2333687
[7] http://www.righto.com/2012/10/a-dozen-usb-chargers-in-lab-apple-is.html

Calculations Use

1 charge a day

The energy for one charge a day was also calculated with the charger power being 5 W[8]. The battery capacity for the 4S is 1432 mA h[9], the charger efficiency value from before was used.

$$= Energy = \frac{Battery\ Capacity \times Voltage}{Charger\ Efficiency}$$

$$= \frac{1.432 \times 5}{0.74}$$

$$= 9.68\ Wh = \frac{9.68 \times 60 \times 60}{10 \times 10^6} = 0.035\ MJ$$

The value for daily energy is then multiplied by the life-time of the phone (2.5 years) to find total energy.

$$= Daily\ Energy \times Days\ per\ year \times Lifetime$$

$$= 0.035 \times 365 \times 2.5$$

$$= 31.93\ \text{MJ}$$

Charger Left plugged in

A calculation for energy used if the charger was left in the wall unplugged for the products life using 0.5W[10] was also done.

$$P \times T = 0.5 \times (60 \times 60 \times 24 \times 365 \times 2.5) = 39.42\ MJ$$

Data Energy consumption

Calculations were also made to find the energy consumed in using WiFi and cellular Data. The Average data use on a phone is 31.4 GB[11], with cellular data using 2.9 GB[12] of this, leaving 28.5 used on WiFi. Wifi consumes 0.06 kW h/GB[13] and 3G cellular (no 4g or 5g on 4S) consumes 2.9 kW h/GB[14].

$$Energy = Wifi\ Use \times Consumption + 3G\ Use \times Consumption$$

$$= 28.5 \times 0.06 + 2.9 \times 2.9$$

$$= 10.12\ kWh/month = 36.4\ MJ/month$$

$$Lifetime\ usage = Usage/month \times Lifetime$$

$$= 36.4 \times 12 \times 2.5 = 1093\ MJ$$

Summary

All energy values for iPhone 4S use are summarized below: (this is assuming the user unplugs the charger after charging)

	Light Usage (MJ)	One Charge Daily (MJ)	Heavy Usage (MJ)
Usage	22.63	31.93	62.26
Usage + Production + Transport	278.43	287.73	318.06
Including Data Consumption	1371.43	1380.73	1411.06

We can see that the data usage is a huge contribution to embodied energy.

[8] https://www.digitalsave.co.uk/apple-5w-usb-power-adapter.html?gclid=CjwKCAiAq8f-BRBtEiwAGr3DgWJQQCCx-w9AAyhxBeuFIPFTcPbxM0--gUhcRVRXN-KL6KmfF_77RdxoCPycQAvD_BwE
[9] https://www.gsmarena.com/apple_iphone_4s-4212.php
[10] https://michaelbluejay.com/electricity/vampire.html#:~:text=Most%20modern%20devices%20use%20no,uses%20 11%2C040%20kWh%20per%20year.
[11] https://www.fiercewireless.com/wireless/alarming-unlimited-data-usage-31-4-gb-per-month-and-rising
[12] https://www.ofcom.org.uk/__data/assets/pdf_file/0020/117065/communications-market-report-2019.pdf
[13] https://onlinelibrary.wiley.com/doi/pdf/10.1111/jiec.12630
[14] https://archive.thinkprogress.org/does-your-iphone-use-as-much-electricity-as-a-new-refrigerator-not-even-close-4a5e0ab41a13/