Article

USA carbon footprints of grills, by fuel & grill type, 2022-27

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Abstract: Grill-specific footprints for common fuels/grill types in the USA are estimated from public information and data from a major grill manufacturer. These are a function of both 1) a fuel's footprint and 2) a grill's efficiency of cooking. In 2022, grill-specific footprints vary by 9:1. A typical gas grill is highest at 3.6 lb CO_2e/grill session, nine times that of a wood-pellet grill, lowest at 0.4 lb. Charcoal briquettes, electricity and super-efficient gas grills come in-between. Pellets are lowest, because they are made from waste wood and their production burden is modest. Electricity has the highest fuel footprint, yet the second-lowest grill-specific footprint, thanks to its high efficiency. Briquettes come in fourth, because their production involves fossil gas, and they contain some fossil coal. Grill efficiency is key for gas (natural gas or propane): a typical gas grill has twice the footprint of a super-efficient one. In 2027, with bio substitution, the super-efficient gas grill would move ahead of pellets. Electricity and charcoal could improve but would still place fifth and sixth. The range of grill-specific footprints could fall to 4.5:1, within a much-lower range, the highest footprint in 2027 almost 60% lower than 2022's highest.

Keywords: grills; carbon footprints; carbon intensities; full fuel cycle.

1. Introduction

Outdoor grilling, or barbequing, is a popular means of cooking in the USA. According to a biannual survey of the Hearth, Patio & Barbeque Association[1], the majority of American consumers, 70% of households, own at least one grill. Of those, nearly half own two grills. The authors estimate the total 'grill park' at around 160 million. Grills fired by gas (natural gas or propane) are found in two-thirds of grill-owning households, charcoal in about half, electric in 10-15% and wood pellets in about 10%.

Significant numbers of consumers are trying to live more sustainably. A 2021 opinion poll[2] reports that 22% of US consumers have made major behavior changes and 55% have made modest behavior changes in their life patterns to become more sustainable. Sixty percent of the same consumers say that sustainability is an important criterion in their purchasing – presumably including that of grills.

Carbon footprints are a popular measure of sustainability. Peer-reviewed footprints of grilling have been published for the United Kingdom [1], and a non-peer-reviewed study by the University of Sheffield was published in 2019[3]. For the US, a non-peer-

[1] https://www.hpba.org/ and https://www.hpba.org/Resources/PressRoom/ID/2140/2022-STATE-OF-THE-BARBECUE-INDUSTRY

[2] https://www.businesswire.com/news/home/20211014005090/en/Recent-Study-Reveals-More-Than-a-Third-of-Global-Consumers-Are-Willing-to-Pay-More-for-Sustainability-as-Demand-Grows-for-Environmentally-Friendly-Alternatives

[3] https://www.sheffield.ac.uk/sustainable-food/news/typical-summer-bbq-releases-more-greenhouse-gas-emissions-80-mile-car-journey

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reviewed comparison of charcoal briquettes and gas was done in 2008[4]. Other, informal investigations appear from time to time in the popular media[5]. This paper is believed to be the first peer-reviewed, comprehensive footprint for grilling in the US.

2. Materials and Methods

This study has estimated a 'grill-specific' footprint in 2022 that is a function of:

- A fuel footprint: carbon-dioxide-equivalents emitted per unit of fuel energy consumed; and
- A cooking footprint: the time required and efficiency of heat delivery by each grill type.

Inputs to these are reviewed in the following two subsections. A third subsection presents a possible scenario for fuel footprints in five years' time, in 2027.

2.1. Fuel footprints 2022

The fuels are presented in alphabetical order: charcoal, electricity, hydrogen, natural gas, propane and wood.

Charcoal briquettes

Kingsford charcoal briquettes are the leading seller in the USA, according to several sources, accounting for well over 50% of total physical volume. So, this has been used as proxy for all charcoal briquettes. Their composition (Table 1) has been estimated from several sources: a video from 2001 of a Kingsford factory[6] that appears to be located on or next to an open-pit coal mine; correspondence of Kingsford with members of the California BBQ Association from around 2001[7]; a Kingsford safety data sheet from 2016[8]; and a material analysis of 74 brands of briquettes[9] by [2]. Eric Johnson also corresponded with the Dr A Drobniak, corresponding author of [2], who now works for the Indiana Geological & Water Survey. Based on all that, the weighted lower heating value (LHV) of a briquette (Table 1) was used to iteratively estimate composition, which came out identically to Kingsford's reported LHV of 22.6 MJ/kg, or 9,700 BTU/lb[10].

Table 1: Composition of Kingsford charcoal briquettes

Component	Weight %	LHV, MJ/kg	Weighted LHV
Charcoal	70%	28	19.6
Brown coal	9%	17	1.53
Limestone	15%	3.2	0.48
Sawdust	5%	19	0.95
NaBorate	1%	0	0
Briquette	100%		22.6

[4] Personal Communication, 2008. C emissions from BBQ grills. Tristram O West. Environmental Sciences Division, Oak Ridge National Laboratory, Tennessee, USA.

[5] Such as https://www.theatlantic.com/science/archive/2021/07/grilling-emissions-environment/619394/

[6] https://www.youtube.com/watch?v=6pFLbB00ZJo

[7] https://www.virtualweberbullet.com/all-about-charcoal/ reproduces the information, which was originally posted by Kingsford. This original was verified by the authors at https://archive.org/web/

[8] https://images.homedepot-static.com/catalog/pdfImages/8d/8d5b38a6-5b61-44a7-903b-3574bcd966f5.pdf

[9] Including 3 samples from Kingsford.

[10] http://www.usscouts.org/scoutcraft/charcoal_powered_water_heater.asp

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About 85% of the pre-combustion footprint (Table 2) comes from the production of charcoal, which includes the briquetting process. This does not include the emissions of the charcoal pyrolysis itself, but of the various operations around that (as shown in the Kingsford video). Because briquettes are made from waste wood, that wood is considered carbon-neutral at its point of collection.

Table 2: Pre-combustion footprint of Kingsford charcoal briquettes

Component	GHG factor kg CO2/ kg fuel	Weight[11] kg	Weighted footprint kg CO2/kg	Footprint sources
Charcoal	1.23	0.70	0.861	ecoinvent: charcoal, at plant, BaseCase
Brown coal	0.34	0.09	0.031	ecoinvent: Hard coal mix, at regional storage/UCTE U
Limestone	0.01	0.15	0.002	Average of ecoinvent and [3]
Sawdust	0.17	0.05	0.008	Wood pellets, u=10%, at storehouse/RER U
NaBorate		0.01	0	NA
Briquette		1.00	0.902	

The footprint comes out at 0.902 kg CO2e/kg briquette, or 0.093 lb CO2e/kBTU or 93 lb CO2e/mmBTU briquette.

About 85% of the combustion footprint (Table 3) comes from burning of the fossil coal component, with the remainder coming from burning of the limestone. The charcoal and wood are assumed to be carbon neutral.

Table 3: Combustion footprint of Kingsford charcoal briquettes

Component	GHG factor kg CO2/ kg fuel	Weight[12] kg	Weighted footprint kg CO2/kg	Notes
Charcoal	0	0.70	0	Assumed carbon neutral
Brown coal	3.67	0.09	0.33	100% carbon to CO2
Limestone	0.44	0.15	0.066	100 CaCO3 + Heat --> 56 CaO + 44 CO2
Sawdust	0	0.05	0	Assumed carbon neutral
NaBorate	0	0.01	0	NA
Briquette		1.00	0.396	

The footprint comes out at 0.396 kg CO2e/kg briquette, or 0.041 lb CO2e/kBTU or 41 lb CO2e/mmBTU briquette.

Electricity

Electricity is assumed to be 'at the plug' closest to a residential grill. Electricity is defined as the average supplied in the US. According to the US Energy Information

[11] From Table 1

[12] From Table 1

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Administration[13], the fuel mix for this is approximately: 40% gas; and 20% each for coal, nuclear and renewables.

According to the current fuel mix, the pre-combustion footprint (Table 4) comes out at 0.025 lb CO2e/kBTU or 25 lb CO2e/mmBTU.

Table 4: Pre-combustion footprints, US electricity (lb CO2e/mmBTU)

Fuel	Weighted average footprint	Source
Coal	7.07	ecoinvent
Nuclear	0.72	UN Economic Commission for Europe
Gas	16.71	National Energy Technology Laboratory (US)
Renewables	0.72	UN Economic Commission for Europe
Sum	25.23	

Using the same fuel mix and the US-average GHG factors published by the US Environmental Protection Agency (EPA)[14], the footprint of American electricity is 403 g CO_2e/kWh, which converts to 0.261 lb CO_2e/kBTU or 261 lb CO_2e/mmBTU.

This figure can vary considerably by region. In the southeastern SERC grid[15] that has the highest footprint in the continental US, the electricity footprint is 724 g CO_2e/kWh, which converts to 0.468 lb CO_2e/kBTU or 468 lb CO_2e/mmBTU. In the upstate New York NPCC grid that has the lowest footprint in the US, the electricity footprint is 106 g CO_2e/kWh, which converts to 0.068 lb CO_2e/kBTU or 68 lb CO_2e/mmBTU.

National footprints of electricity are often used in carbon footprints of products. However, many product footprints assume electricity is supplied by a specific grid or even a specific generating plant[16]. There is no set rule or convention as to which should be used.

For electricity, a 10% loss – a typical value in footprint models – has been assumed for transport and distribution to the point of use.

(Green) hydrogen

Green hydrogen is presumed to be made from electrolysis of water powered by renewable electricity. Hydrogen grilling is not yet commercial. Given its minor role and the uncertainty surrounding its eventual, commercial footprint, the authors have simply taken the working definition of the European Union[17], which is that to be classified as 'green', hydrogen must have a footprint of 85 lb CO_2e/mmBTU or less.

Natural gas

Natural gas in the US is typically around 95% methane plus some ethane, carbon dioxide and traces of other hydrocarbons and nitrogen.

The US-national average pre-combustion footprint for natural gas is 0.042 lb CO_2e/kBTU or 42 lb CO_2e/mmBTU LHV [4]. Natural gas pre-combustion footprints have surfaced in the mainstream media in recent years, particularly with respect to 1) emissions

[13] https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php

[14] Published on 15 Sept 2021 at https://www.epa.gov/climateleadership/ghg-emission-factors-hub

[15] Alabama, Georgia, Mississippi, Missouri, North Carolina, South Carolina, Tennessee, and portions of Arkansas, Illinois, Kentucky, Louisiana, Oklahoma, Texas, Virginia, and Florida.

[16] This is supported by the practice of selling 'green electricity'. Customers can buy low-carbon power, which is delivered in the form of a carbon credit, not in actual 'green' electrons.

[17] https://www.fch.europa.eu/news/clarification-compliance-certifhy-green-hydrogen-criteria-fch-ju-projects

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from fracking and 2) fugitive emissions of methane throughout the supply chain. The NETL data [4] take full, state-of-the-art account for this.

The stoichiometric output of carbon dioxide from burning of methane was applied: 0.136 lb CO_2e/kBTU or 136 lb CO_2e/mmBTU LHV. A GHG factor published by the US Environmental Protection Agency (EPA)[18] was not applied, because it is nearly 15% lower – which does not seem physically plausible.

Propane

Propane in the US consists mainly of, not surprisingly, propane, plus small amounts of other hydrocarbons and carbon dioxide. It is produced both as a byproduct of oil refining and as a byproduct of natural-gas processing[19]. Internationally, propane is usually designated as liquified petroleum gas (LPG), which can be mainly propane, mainly butane or some mix of the two.

The most recent, authoritative report of propane's US footprint comes from California's Air Resources Board as part of its Low Carbon Fuels Standard[20]: 194 lb CO_2e/mmBTU. The stoichiometric output of carbon dioxide from burning of propane was applied as the combustion footprint: 0.151 lb CO_2e/kBTU or 151 lb CO_2e/mmBTU. The remainder is the pre-combustion footprint of 0.043 lb CO_2e/kBTU or 43 lb CO_2e/mmBTU.

Wood pellets and wood logs

Wood comes from countless species of trees. So do wood pellets, which can also come from 'woody biomass'. Those used in grilling come from waste/residue wood, not from stem wood. Lower heating values of 19.6 and 20 MJ/kg are used for pellets and air-dried wood [5]. Combustion emissions are 202 lb CO2e/mmBTU [1]. Pre-combustion footprints are taken from ecoinvent: pellets from the process 'Wood pellets, u=10%, at storehouse/RER U'; and logs from 'Logs, hardwood, at forest/RER U'. European datasets were used, because no equivalent US datasets are readily available. From inspection of the data, it is believed that European and US figures would be very similar.

2.1. Cooking footprints 2022

Non-confidential efficiencies and time periods of fire-up and cooking were supplied through Alex Gafford by a leading manufacturer of grills (Table 5).

[18] Published on 15 Sept 2021 at https://www.epa.gov/climateleadership/ghg-emission-factors-hub

[19] Propane and butane must be removed from natural gas, before the gas is charged to a high-pressure pipeline, because under high pressure they will condense. Those liquids would cause problems in pipeline operations. Most butane in the USA ends up in gasoline or petrochemicals.

[20] https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities

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Table 5: Grill efficiencies and fire-up/cook times

Grill type	BTU/ hr max	BTU/ hr min	BTU/ hr sq in	Fuel	Ignition min	Warm up min	Cook min	Notes
Electric high heat	5975	N/A	*20*	*0*	0	15	30	
Electric low heat	5975	N/A	*20*	*0*	0	15	30	
Electric average heat	5975	N/A	*20*	*Electricity*	0	15	30	300 sq in, thermostatic control, assume operating rate at 2/3 max
Typical convective gas grill at 30,000 BTU/hr.	30000	13500	*100*	*Propane*	0	15	30	300 sq in, assume operating rate at avg of max rate and min rate
Improved IR gas grill at 22,500 BTU/hr.	22500	13500	*75*	*Propane*	0	15	30	300 sq in, assume operating rate at avg of max rate and min rate
Super efficient IR gas grill at 15,000 BTU/hr	15000	9000	*50*	*Propane*	0	10	30	300 sq in, assume operating rate at avg of max and min
Pellet Smoker/Grill	40000	N/A	*157*	*Pellets*	10	10	40	254 sq in, thermostatic control, assume opeating rate at 1/2 max
Charcoal Grill	N/A	N/A	N/A	Charcoal briquettes	0	15	75	254 sq in, no control; assume 2.2 lb @ 9700 BTU/lb, i.e. 1 kg charcoal, consumed over 90 minutes

From these, heat fluxes for a grill session were derived (method is shown for gas/electric grills in Figure 1 as an example, fluxes for all grills are shown in Table 6).

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Figure 1: Gas/electric heat flux

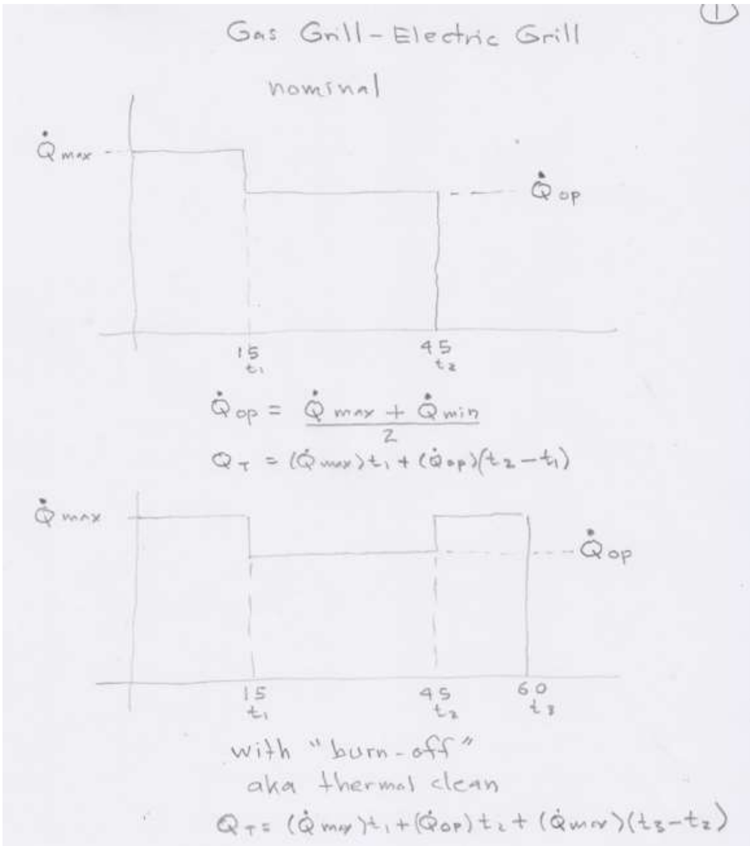

Table 6: Heat fluxes, by grill type

Grill type	BTUh max	BTU/ cycle aka Q total	kBtu/cycle
Electric high	5975	3485	3.5
Electric low	5975	3485	3.5
Electric average	5975	3485	3.5
Typical gas grill	30000	18375	18.4
Improved gas grill	22500	14625	14.6
Super-efficient gas grill	15000	8500	8.5
Pellet	40000	20000	20.0
Charcoal	N/A	14227	14.2

2.2. Grill footprints in 2027

So how might fuel footprints be reduced in the coming five years? Plausible scenarios for each of the fuels were estimated, based on best efforts analysis and best-available data.

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No-coal charcoal?

The only obvious reduction possibility for briquettes is a reformulation of its current composition by the removal of fossil coal and its replacement with charcoal from wood. This is not an obvious possibility – it could be that fossil coal is critical to customer acceptance or production cost or some other requirement.

Electricity decarbonised

US power has steadily shifted to renewable fuels for years past and will do for years to come. According to the US Energy Information Administration (USEIA)[21], the renewables share of electricity was: 10% in 2010; is now 24%; and by 2027 will reach 32%. The average footprint of American power[22], USEIA projects, will drop in 2022-2027 by 23%.

Green hydrogen

Because there are so many uncertainties about green hydrogen, an alternative case for 2027 has not been projected. The main alternative is: will green hydrogen happen or not? If it does, the best estimate for 2027 is the same as for 2022.

Renewable gas

From reports in the media, renewable gas – i.e. biogas – is booming. Indeed it is, but from a very low base globally and in the USA. According to interpolation of data from [6], biogas accounts for 0.07% of all gas in the world's grids. The IEA projects this to climb to 0.5% by 2030 [6][23]. So, steep growth (mainly in Asia), but still a small presence overall. Moreover, only about 10% of biogas is upgraded to biomethane and injected to the natural gas grid – the rest is used for heating or electricity generation by the biogas producer. The plausible scenario, therefore, is that the footprint of gas-grilling in the US will not change by 2027.

rPropane

Renewable propane has been available for about 6-7 years now. Its typical footprint is about 80% less than that of fossil propane [7] [8]. Several propane (LPG) distributors in Europe[24] offer rPropane in cylinders that can be used for grilling. There is considerable production of rPropane in the USA. Some 250 million tonnes/year will be made in 2022, and this will probably break 1 million tonnes/year by 2025 [9]. That could be enough to justify an effort to divert some of it into grilling. A prime target would be California distributors, who already sell it into the Autogas market [8].

Wood

The rules of carbon accounting can be confused, when it comes to wood burning. A decade or two ago, wood was commonly considered to be carbon neutral. "You burn the tree; the tree grows back"[10]. Increasingly, this view is challenged, because it suggests that if someone cut down all the world's forests and burned them, overnight, this would cause zero carbon emission. So, there have been challenges. One of the most prominent was the Manomet Project[25] in Massachusetts that blocked construction of a pellet-fired power plant. 'Pellet Wars' have also raged in Europe; nonetheless, pellet imports for European power generation are growing dramatically. In the past year, the International

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[21] https://www.eia.gov/outlooks/aeo/

[22] US-average power footprints published by the USEIA are about 10% lower than those published by USEPA (Section **Error! Reference source not found.**). For these kinds of statistics, that means they are effectively equal.

[23] Also see https://iea.blob.core.windows.net/assets/03aeb10c-c38c-4d10-bcec-de92e9ab815f/Outlook_for_biogas_and_biomethane.pdf

[24] For instance, https://www.calorgas.ie/cylinders/biolpg-cylinder

[25] https://www.manomet.org/project/woody-biomass-energy/

Energy Conservation Code (IECC), a building code created by the International Code Council in 2000, was amended to exclude wood from its previous classification as a 'renewable' fuel[26]. So far this has been only for commercial buildings: a similar proposal for residential buildings is still in debate. Nonetheless, a 'carbon-neutral presumption' has been and is being challenged. So, there is some possibility of a public backlash against pellets. Or even wood. However, the footprint impact is difficult or impossible to quantify, and it is even more difficult to project a difference from today to 2027 – so it is assumed that accounting rules will not change by then.

3. Results

Grill-specific footprints for 2022 were calculated by: multiplying 1) the fuel footprint (carbon emission per energy unit of a given fuel) times 2) the required energy flux of a given grill type. These are presented from lowest to highest (Figure 2), and for reference, the fuel-only footprints are presented alongside. Fuel-only footprints were also broken out by life-cycle stage (Figure 3).

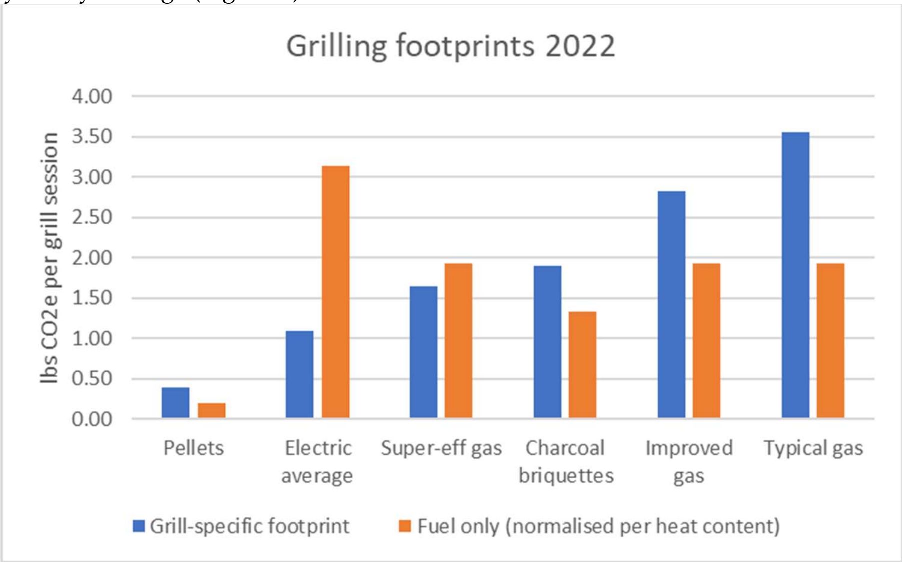

Figure 2: Carbon footprints for grills, grill-specific and fuel-only, USA 2022

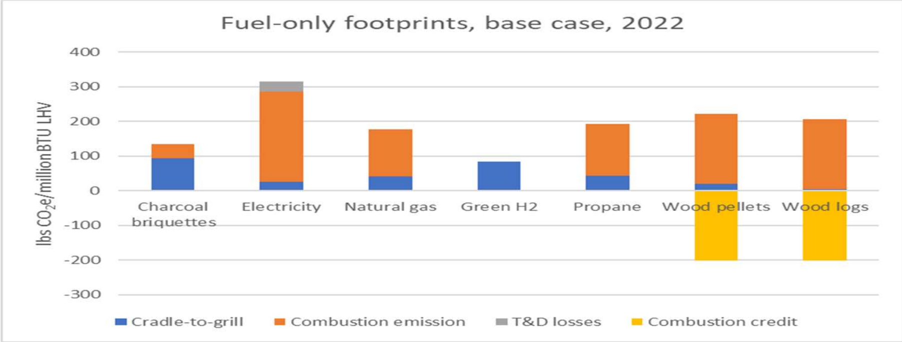

Figure 3: Carbon footprints for grills, fuel-only by life-cycle stage, USA 2022

[26] If it's not renewable, what is it? The revised code does not say, other than it is not renewable.

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Using the same method as for 2022, possible footprints were calculated for 2027 (Table 7). They are presented alongside the 2022 ones for comparison.

Table 7: Carbon footprint rankings, by fuel, 2022 base case vs alternative 2027 case

Base case 2022		Possible case 2027	
Grill fuel	*lb CO2e/ mmBTU LHV*	***Grill fuel***	*lb CO2e/ mmBTU LHV*
Wood logs	4	Wood logs	4
Wood pellets	20	Wood pellets	20
Green hydrogen	85	Renewable propane	39
Charcoal briquettes	134	Biomethane (gas)	44
Natural gas	177	Green hydrogen	85
Propane	194	Charcoal briquettes	107
Electricity	314	Electricity	255

4. Discussion

The variation of grill-specific footprints is broad, and rankings could change considerably from 2022 to 2027 (Table 7). These are discussed in subsequent subsections.

Another remarkable finding is that both fuel footprints (which are well known) and cooking footprints (less well known) are critical. The importance of efficiency – the key to the cooking footprint – is seen obviously in gas grills. A super-efficient gas grill's footprint is less than half that of a typical one's (Figure 2), despite using the exact same fuel. The low-efficiency electric grill has a footprint four times that of a high-efficiency, again, using the same fuel.

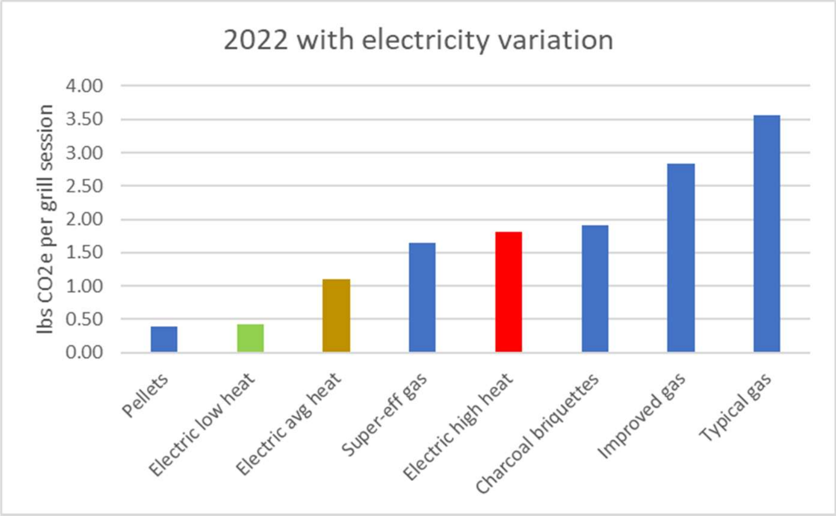
4.1. Footprints 2022

Today in 2022, grill-specific footprints for US grills vary by a factor of 9:1. A typical gas grill's footprint is highest; its 3.6 lb CO_2e/grill session is nine times that of a pellet grill, which comes in lowest at 0.4 lb. Charcoal briquettes and electricity and super-efficient grills come in-between.

Pellets are a clear winner, with a footprint one-third that of second-place electricity. This is because they are made from wood considered to be carbon neutral, and their production footprint is modest. Electricity has the highest fuel footprint, yet the second-lowest grill-specific footprint, thanks to the high efficiency of its grill. Perhaps surprisingly, charcoal briquettes come in fourth, even though they are composed mostly of wood that is considered carbon neutral. Their production involves use of fossil gas, and they contain some fossil coal, which of course is not carbon neutral. Grill efficiency also makes a big difference for gas (either natural gas or propane): a typical gas grill has twice the footprint of a super-efficient one.

The wild card here is electricity. Generating footprints of regional grids in the continental US vary by a factor of four, from high in the coal-dominated southeast to low in hydro-heavy upstate New York. The US average is about halfway in-between. At its low, electricity's footprint is 0.43 lb CO_2e/grill session, almost equal to that of pellets (Figure 4). At its high of 1.82 lb CO_2e/grill session, electricity's footprint is about equal to briquettes'. The other fuels have some variation, but not nearly that of electricity, and not enough to significantly change rankings.

Figure 4: Grill-specific carbon footprints for grills, with high-low-average electricity, USA 2022

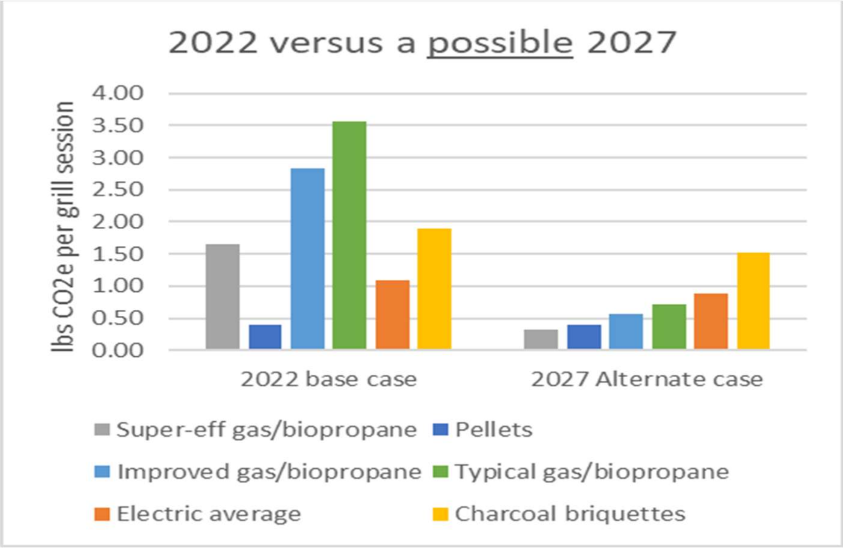


4.2. Footprints 2027

Five years from now, three significant differences could ensue (Figure 5):

1) rankings could change considerably;
2) footprint variation could narrow from 9:1 today to about 4.5:1; and that
3) within a much-lower range, the highest footprint of in 2027 of 1.5 lb CO2e/grill session coming in almost 60% lower than 2022's highest of 3.6 lb.

Figure 5: Grill-specific carbon footprints for grills, USA 2022 and alternate 2027



If biopropane were substituted for today's fossil propane, the super-efficient gas grill would move slightly ahead of pellets, with its two less-efficient incarnations coming in

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third and fourth[27]. Electricity lowers its footprint 20%, but still is relegated to fifth. Charcoal also makes a 20% improvement but comes in last.

The 2027 case is only a scenario, of course, but the possibilities are plausible. That said, the rankings could stay relatively similar to today's. Only electricity is almost certainly destined to lower its footprint; for its competitors, improvement is a choice that suppliers can make (or not). Despite improvement, electricity will still in 2027 have the kind of variation it has today: its high will be in the range of a briquette footprint; its low will be competitive with the footprints of pellets and biopropane.

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10. Johnson, E. Goodbye to Carbon Neutral: Getting Biomass Footprints Right. *Environ. Impact Assess. Rev.* 2009, *29*, 165–168.

[27] Similar results would come from substitution of natural gas with biomethane, but this is less available to grills, so the biopropane case has been presented.