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Sustainability Choices when Cooking Pasta

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ABSTRACT

Everyday activities requiring electrical or thermal power imply sustainability decisions. Choices for different energy sources, which equipment to use, and the timing of activities have major implications for CO_2 emissions. Being aware of each of them and accounting for their impact is nearly impossible. First, it is unclear how to assess the sustainability footprint of a decision; second, the complexity of the implications of all such decisions is overwhelming. To make things more concrete, we consider a simple as well as common task: cooking a dish of pasta. We measure the sustainability of the decisions involved in terms of CO_2 emissions and we use historical data of German CO_2-emission intensity calculated with both the average method and the marginal one. We find that starting from hot or cold tap water can imply up to 35% difference in emissions, depending on the timing and the chosen equipment. However, the complexity and size of information involved in such sustainability choices require the adoption of digitalized and automated systems, which, in turn, raises questions about user acceptability and (mis)trust in such technologies.

CCS CONCEPTS

• **Hardware** → **Impact on the environment**; *Smart grid*; • **Information systems** → *Decision support systems*; • **Computing methodologies** → *Model development and analysis*; • **Applied computing** → Sociology.

KEYWORDS

Sustainability, Complexity, Automation, Carbon emissions, Marginal method

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1 HOT OR COLD WATER?

In our everyday lives we constantly take sustainability decisions, most often implicitly. Take the simple task of cooking a dish of pasta; a daily task for 63% of the Italian population and a bi-weekly task for an average German household. When taking a pot to the sink to fill it with water for boiling the pasta, the person cooking is faced with the choice of starting with either hot or cold water. People may just take water without thinking, or they could be using hot water with the intention of speeding up the process. Which is the environmental impact of such a choice? We take many such decisions on a daily basis. Do we set the thermostat to have the house preheated by the time we arrive or do we wait to turn on the heater once we are at home? Do we start an half-empty dish washer with a short, low-temperature program or do we run a high-temperature one once it is entirely filled? Do we do the laundry in the middle of a sunny day or do we do it in the evening when almost no renewable energy is available? Being aware of each of the choices and accounting for their environmental impact is hardly feasible. People's perceptions of the environmental impact of their behavior is not always accurate [1, 2, 13] and the complexity of the implications of all such decisions is overwhelming [14]. Moreover, there is no standard method to assess the environmental impact of energy consumption. For instance, the CO_2-emission intensity (EI) tied to the use of electricity can be calculated using either the average method or the marginal one. The former is based on the energy mix [9], while the latter requires the identification of the power plant(s) reacting to a change in the electricity demand [10].

Developments and growth in digitalization and automation systems can support individuals in making the "right" sustainable decision in such cases. Digitalization provides high-frequency, precise data which is relevant for making sustainability choices; think of smart meters, smart thermostats, or automobile on-board computers. Automation can operate in complex scenarios on behalf of a user who simply can state high level goals; for instance minimizing the environmental impact with respect to home heating or automobile driving behavior.

In this paper, we model the process of pasta cooking, with the aim of demonstrating how complex is to reduce the environmental impact of such an ordinary task. We use the data of the German EI of 2018 and we determine cooking patterns according to several combinations of common equipment used to cook the pasta. We evaluate and compare the environmental impact of the different cooking methods; the difference in emissions is shown to be as high as 35%. Finally, we discuss how to move from such insights to automation systems to support the average user in making sustainable choices.

2 ENERGY MODEL

According to Italian cookbooks and tradition, cooking pasta entails using 1 liter of water per 100 g of dried pasta, which is generous amount of one person. For this study, we assume boiling 5 liters of water in order to cook 500 g of dried pasta. The water has to be

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Table 1: Efficiency factors of the equipment involved in the process of cooking pasta.

Equipment	Efficiency %	Task	Energy consumption Wh/100 ml
High efficiency gas water heater	95	Preheating	
Electric water heater	97	Preheating	
Electric kettle	95	Boiling	10.4 [12]
Microwave oven	63	Boiling	20.7 [12]
Ceramic hob	65	Boiling/cooking	15.3 [12]
Solid hot plate	70	Boiling/cooking	14.2 [5]
Induction hob	85 [11]	Boiling/cooking	11.6
Gas hob	52 [11]	Boiling/cooking	19.0

brought to 100°C, and then the pasta can be thrown in. Depending on the shape, freshness, and thickness of the pasta, the water with the pasta has to be kept boiling for anywhere between few minutes to a quarter of an hour. Hence, there are two main phases in the process: (1) bringing the water to its boiling temperature; and (2) keeping it boiling to cook the pasta. Several options are possible for bringing the water from room temperature to its boiling temperature to cook the pasta: using a pot on ceramic hob with radiant heating, a kettle, a microwave, a gas stove, a solid hotplate, or an induction hob. Moreover, we can use either cold or preheated tap water to bring the water to the boiling temperature, as further detailed in Appendix A.

The types of equipment can be divided in two broad categories: equipment that can only be used for water heating, and equipment that can be used for both water heating and pasta cooking (see Table 1). In particular, an electric kettle and a microwave oven can only be used to heat the water; once the water is boiling, it has to be poured into a pot and another equipment has to be used. Table 1 gives an overview of the energy efficiency of the different types of equipment and shows that 12 combinations of equipment can be used to cook the pasta. Moreover, considering the choice to use cold or preheated water to start with, and two possible types of water heaters, the total number of possible combinations to cook half a kilo of pasta is 48. We call these combinations "patterns." The 48 patterns can be clustered into nine classes, according to the energy carriers used to boil the water and to cook the pasta. Given that E stands for electricity and G for gas, we can define three classes without preheating, i.e., "EE," "GG," and "EG," where the first letter refer to boiling and the second to cooking, and six classes with preheating, i.e., "GEE," "GGG," and "GEG," and "EEE," "EGG," and "EEG," where the first letter refers to preheating.

The patterns used for cooking pasta are thus based on the choices of the user. Equipment availability choices are long-term, infrastructural ones; cooking modalities based on available equipment are short-term, operational decisions. The combination of such decisions is summarized by a pattern, in turn determining the environmental impact of the cooking method. More details about the equipment are provided in Appendix B.

3 CO_2-EMISSION INTENSITY

When we use the electricity coming from the main grid, the amount of CO_2 emitted to generate a kWh, referred to as CO_2-emission intensity (EI), can be determined with two methods. The average method determines the EI based on the actual generation mix. For instance, given a certain amount of power to be produced, the average-EI on a sunny, windy day is likely to be significantly lower than on a windless and cloudy one, when almost all the power is generated by plants burning fossil fuels. This factor can be defined either as a constant (e.g., [15]) or as a hourly value (e.g., [4, 9]).

Yet, when a change in the electricity demand occurs, not all the power plants adjust their generation output evenly. This is due to several factors, such as generation capacity, ramp-rates, costs, and market dynamics. The power plant that increases or decreases its generation is referred to as marginal and it may correspond to a single physical power plant, to a group of power plants, or to a cross-border flow from/to a neighboring country. The marginal power plant method thus estimates the marginal-EI as equal to the emission factor of the marginal power plant (or as a combination of the emission factors of the group of marginal power plants), which may vary from hour to hour [10].

We take a concrete example to compare the CO_2 emissions of different methods for cooking pasta, using data of the German power system in 2018. In this year, the average-EI associated with electricity generation varied between 122 gCO_2/kWh and 563 gCO_2/kWh [8]. On the other hand, the marginal-EI varied between 332 gCO_2/kWh and 589 gCO_2/kWh. EI values may not only significantly vary during the year, but also during the day. Moreover, it may happen that an increase in the average-EI corresponds to a decrease in the marginal-EI and vice versa. We show the hourly EI calculated with the two methods for a week in July 2018 in Fig. 1 [8]. Yet, when energy is delivered to the household as gas, then the EI can be taken as constant and equal to 288 gCO_2/kWh [7].

4 USER CHOICES EFFECTS ON CO_2 EMISSIONS

We can now match the ways of cooking pasta having their relative efficiency with the CO_2 emissions.

Considering the marginal-EI of electricity under three scenarios, Table 2 shows the CO_2 emissions of cooking pasta for the nine classes of equipment combinations defined above. For each EI scenario and class, we report the CO_2 emissions for the equipment combinations with the highest (best), lowest (worst), and average energy efficiency. Additionally, we provide the differences in CO_2 emissions when preheating the water compared to starting to cook with cold water. When we use only electricity ("EE") with the most energy efficient equipment (i.e., boiling water with the kettle and

Table 2: CO_2 emissions in grams for nine classes of equipment combinations with different marginal-EI (mar-EI). CO_2 emissions are reported for the equipment combinations with the best, worst, and average energy efficiency. In brackets, variation in CO_2 emissions due to preheating the water with an electric or gas water heater compared to starting with cold water.

	mar-EI=332 gCO_2/kWh			mar-EI=466 gCO_2/kWh			mar-EI=589 gCO_2/kWh		
	Best	Avg.	Worst	Best	Avg.	Worst	Best	Avg.	Worst
EE	273	338	392	384	475	550	485	600	696
GEE	264 (-3%)	309 (-9%)	347 (-12%)	346 (-10%)	409 (-14%)	462 (-16%)	421 (-13%)	501 (-16%)	567 (-18%)
EEE	272 (–)	317 (-6%)	355 (-10%)	382 (-1%)	445 (-6%)	498 (-10%)	482 (-1%)	563 (-6%)	629 (-10%)
EG	316	359	403	385	447	508	449	527	605
GEG	306 (-3%)	332 (-8%)	356 (-11%)	347 (-10%)	383 (-14%)	420 (-17%)	385 (-14%)	431 (-18%)	476 (-21%)
EEG	314 (-1%)	340 (-5%)	366 (-9%)	383 (-1%)	419 (-6%)	456 (-10%)	446 (-1%)	492 (-7%)	538 (-11%)
GG		416			416			416	
GGG		366 (-12%)			366 (-12%)			366 (-12%)	
EGG		374 (-10%)			402 (-4%)			428 (+3%)	

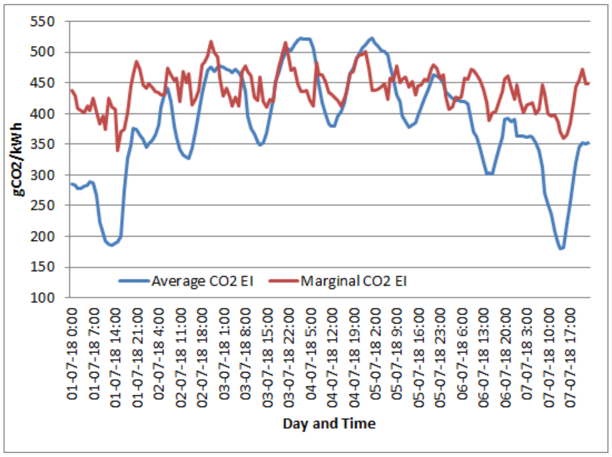

Figure 1: German average and marginal CO_2-emission intensity for the first week of July 2018

cooking pasta on the induction stove), emissions can almost double owing to the variation of marginal-EI. As the EI of gas is constant, CO_2 emissions will vary less across time when electricity is used for boiling and a gas hob for cooking the pasta ("EG"), limiting the difference between the scenarios with lowest and highest electricity marginal-EI to a factor 1.5. When only gas is used to boil the water and cook the pasta ("GG" and "GGG"), CO_2 emissions are constant across time and do not change with different scenarios, as no electricity is used. The reduction in emissions obtained by preheating the water in a high-efficiency gas water heater rather than an electric one depends on the marginal-EI at that time. Yet, as the EI of gas is always lower than the one of electricity, preheating the water with the gas water heater is always the most sustainable choice. Indeed, using the gas water heater reduces CO_2 emissions between 3% and 21% (i.e., -9 gCO_2 to -129 gCO_2). On the other hand, an electric water heater limits the emission savings to 12% (i.e., -50 gCO_2) and, when the marginal-EI is very high, it can even increase the emissions.

We consider now the average-EI of electricity. The CO_2 emissions of cooking pasta for the nine classes of equipment combinations and three energy-mix scenario are summarized in Table 3. When using only electricity, emissions can increase up to 4.6 times due to the large variation in time of the average-EI. When the average-EI is low, the CO_2 emissions associated with using gas in the cooking phase are up to 3 times higher than using electricity. The impact of preheating the water strongly depends on the energy-mix scenario. Using an electric water heater usually results in lower CO_2 emissions compared to starting with cold water; yet, its potential benefits are time-dependent and decrease as the electricity average-EI increases. In fact, although the electric water heater has a higher energy efficiency than the gas one, in fossil fuel-based energy-mix scenarios (i.e., high average-EI) preheating the water with gas is more sustainable than with electricity.

To make this analysis more tangible, consider a person planning to cook half a kilo of pasta on a specific day in Germany, say 1 July 2018. The person can decide to cook it during breakfast and eat it later for lunch, cook it around lunch time, or cook it for dinner. [1] We consider three marginal-EI values, i.e., 405 gCO_2/kWh, 425 gCO_2/kWh, and 445 gCO_2/kWh, and three average-EI ones, i.e., 288 gCO_2/kWh, 188 gCO_2/kWh, and 348 gCO_2/kWh, which correspond to the EI at 6 am, 12 pm, and 6.30 pm, respectively. Moreover, we assume that the best equipment pattern is used, that is, the water is boiled using the kettle and the pasta is cooked using an induction hob. A gas or electric water heater may be used to preheat the water.

The CO_2 emissions calculated with the marginal-EI and with the average-EI are summarized in Table 4 and Table 5, respectively. The results show that the most sustainable choice may vary depending on how the EI are estimated. Indeed, an energy mix largely composed by renewable sources as the one at 12 pm is a good indication for the most sustainable choice when average-EI values are used. Yet, it would be better to cook the pasta in the morning if marginal values are considered. Preheating the water with an electric water

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[1] We do not take into account the emissions related to refrigeration, which may be needed when the pasta is eaten some hours after cooking in order to avoid proliferation of Bacillus cereus.

Table 3: CO$_2$ emissions in grams for nine classes of equipment combinations in three energy-mix scenarios with different average-EI (avg-EI). CO$_2$ emissions are reported for the equipment combinations with the best, worst, and average energy efficiency. In brackets, variation in CO$_2$ emissions due to preheating the water with an electric or gas water heater compared to starting to cook with cold water.

	avg-EI=122 gCO$_2$/kWh			avg-EI=380 gCO$_2$/kWh			avg-EI=563 gCO$_2$/kWh		
	Best	Avg.	Worst	Best	Avg.	Worst	Best	Avg.	Worst
EE	100	124	144	313	387	449	464	573	665
GEE	136 (+35%)	153 (+23%)	166 (+15%)	293 (-6%)	345 (-11%)	388 (-14%)	405 (-13%)	482 (-16%)	545 (-18%)
EEE	100 (–)	116 (-6%)	130 (-10%)	310 (-1%)	362 (-6%)	405 (-10%)	460 (-1%)	537 (-6%)	600 (-10%)
EG	206	222	239	340	391	441	436	510	584
GEG	242 (+17%)	251 (+13%)	261 (+9%)	321 (-6%)	350 (-10%)	380 (-14%)	377 (-13%)	421 (-18%)	464 (-21%)
EEG	206 (–)	215 (-3%)	225 (-6%)	338 (-1%)	368 (-6%)	397 (-10%)	432 (-1%)	476 (-6%)	520 (-11%)
GG		416			416			416	
GGG		366 (-12%)			366 (-12%)			366 (-12%)	
EGG		329 (-21%)			383 (-8%)			421 (+1%)	

Table 4: CO$_2$ emissions in grams associated with cooking pasta on 1 July 2018 using marginal-EI

	mar-EI=405 6 am	mar-EI=425 12pm	mar-EI=445 6.30 pm
EE	334	350	366
GEE	309 (-7%)	321 (-8%)	333 (-9%)
EEE	332 (<-1%)	348 (<-1%)	365 (<-1%)

Table 5: CO$_2$ emissions in grams associated with cooking pasta on 1 July 2018 using average-EI

	avg-EI=288 6 am	avg-EI=188 12pm	avg-EI=348 6.30 pm
EE	237	155	287
GEE	237 (–)	176 (+14%)	274 (-4%)
EEE	235 (<-1%)	154 (<-1%)	284 (-1%)

heater has always a positive effect, although minor. On the other hand, the impact on the emissions of using a gas water heater varies between -9% and +14% depending of the EI used. Moreover, using the average-EI may lead to a significant underestimation of the emissions.

5 CONCLUDING REMARKS

The modeling of a simple daily task such as cooking pasta has shown that a simple choice like using hot or cold tap water is also an implicit environmental choice. Our analysis shows that the impact in terms of CO$_2$ emissions depend on many factors, including the energy carriers used, the efficiency of appliances used, the method used to calculate the EI, and the energy generation mix at a given time and place. In our model, the difference is shown to be as high as 21%, when using the marginal-EI, and up to 35%, when using the average one.

It is important to emphasize that, while the amount of CO$_2$ savings per event might look small (on average, 14 to 66 gCO$_2$ by preheating the water for 500 g of pasta, depending on method used to assess the EI), the combined effect of repeated behavior choices of large groups of people will be significant. Considering that an average tree in central Europe absorbs around 10 kg of CO$_2$ per year [3], 2000 families cooking pasta three times per week and following sustainable choices could reduce as much CO$_2$ as a hectare of trees would absorb in one year by just preheating water.

A simplified model like the one used in this paper is already too complex and populated with information with a volume and variety that are too high to expect a user to be aware of and use it in daily decisions. Fortunately, with the growth in digitalization, personal assistants, and home automation system, one can support the user in effortlessly making sustainable choices throughout the day. Systems like the one we hint in this paper could work by recognizing the user intention to cook pasta when reading a recipe off the Web. The home automation system could recommend to use cold water via a notification or suggest to preheat the water with the electric kettle by turning on a green indicator light. Alternatively, the user could proactively ask an app how to best proceed to reduce one's environmental impact. A key question to explore in future studies is to what extent and under which conditions users find such systems acceptable, and whether they will consistently make use of them.

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A BOILING WATER AND COOKING PASTA

We size the model assuming 5-6 people portion, that is, boiling 5 liters of water in order to cook 500 g of dried pasta. There are two main phases in the process: (1) bringing the water to its boiling temperature; and (2) keeping it boiling to cook the pasta. The model is significantly simplified; for instance, we do not consider the drop in water temperature when the water brought at boiling temperature with an electric kettle is poured into a pot.

Phase 1. Boiling the water. The first step is to choose between cold or preheated water, whose temperature at the tap is assumed to be 15 or 50°C, respectively. If we use cold water, the chosen equipment has to bring the water from 15°C to 100°C. In the ideal case, the required heat is

$$Q_b = m_w \cdot \Delta T \cdot c_w = 5 \cdot (100 - 15) \cdot 1.163 = 494 \text{ Wh} \tag{1}$$

where m_w is the mass of water to be heated, ΔT is the temperature variation, and c_w is the specific heat capacity of water expressed in Wh/kg°C.

If we use preheated water, that is, coming from the home central heating system, the process of boiling it has to be divided in two consecutive steps. First, an ideal gas burning boiler has to provide around $Q_{ph} = 203$ Wh to preheat the water, considering Equation 1 and $\Delta T = (50 - 15) = 35°C$; next, an ideal equipment has to increase the water temperature from 50°C to 100°C, $Q_b = 291$ Wh.

Phase 2. Cooking pasta. Once the water is boiling, we add the pasta, which is at the room temperature of 23°C. The moment it hits the water, the water cools down, while the pasta starts to warm up and cook. The ideal system composed by the water and the pasta reaches an equilibrium temperature T_{eq} that can be calculated according to Equation 2:

$$T_{eq} = \frac{m_p \cdot c_p \cdot T_p + c_w \cdot m_w \cdot T_w}{c_p \cdot m_p + c_w \cdot m_w} = 97°C \tag{2}$$

where m_p, T_p, and c_p are the mass, the temperature, and the specific heat capacity of the pasta, respectively, and T_w is the water temperature. c_p is assumed equal to 0.5 Wh/kg°C [6]. We assume that the pasta needs 9 minutes to cook and that we use a 1800 W burner. First, the temperature of the water-pasta system raises until 100°C, then we supply enough heat for keeping the water at boiling point. In order to increase the system temperature, the required amount of heat is calculated according to Equation 3

$$Q_{c1} = (m_p \cdot c_p + m_w \cdot c_w) \cdot (100 - 97) = 6.065 \cdot 3 \approx 18 \text{ Wh} \tag{3}$$

Bringing the system back to boiling temperature takes around 1 min, given the 1800 W burner. Assuming the pasta needs to cook for 8 more minutes, we have $Q_{c2} = 240$ Wh. At the end, the total amount of heat required for cooking the pasta is $Q_c = 18+240 = 258$ Wh, assuming an ideal system without heat losses.

Moving to a realistic scenario where none of the components of the process has a 100% efficiency, the required heat to boil water and to cook the pasta are as follows

$$Q_{ph,real} = \frac{Q_{ph}}{\eta_b} \qquad Q_{b,real} = \frac{Q_b}{\eta_{eq}} \qquad Q_{c,real} = \frac{Q_c}{\eta_{eq}} \tag{4}$$

where η_b and η_{eq} are the efficiency of the boiler preheating the water and of the equipment used to boil the water and/or cook the pasta, respectively.

B EQUIPMENT

Oberascher *et al.* investigate how the energy consumption of daily food preparation processes, such as boiling water, cooking potatoes, and boiling eggs, can vary according to the chosen equipment and method. The experiments show potential energy savings between 50% and 70% for several activities [12]. With respect to boiling water, the authors of the study compare the energy consumptions of common household appliances, namely cooking pot, electric kettle, and microwave. Carlsson-Kanyama *et al.* measure the electricity consumption for cooking several kinds of food, e.g., dried and fresh pasta, rice, potatoes, [5]. According to the preparation, the efficiency of several devices are compared, as well as the energy demand due to the number of portions. The assumptions made as input for our calculation are based on empirical data from previous published studies. In particular, we consider each type of equipment with respect to the energy that is ideally required to bring 100 ml of water at 15°C to boiling temperature of 100°C, that is, 9.9 Wh. To the best of our knowledge, there is no empirical data on the energy consumptions of boiling 5 l of water, therefore we use the results in [5, 12] for 1 l of water. The energy consumptions for boiling water and the calculated efficiency factors are summarized in Table 1.

Ceramic hob with radiant heating. The required energy for boiling water with a pot with closed lid, referred to as "ideal pot," is 15.3 Wh/100 ml of water, when 1 liter of water is boiled from the initial temperature of 15°C [12]. We calculate the efficiency of this system to be 65%.

Solid, electric, hot plates The required energy for boiling 1 l of water with hot plates, starting from a temperature of 15°C, is around 142 Wh, that is, 14.2 Wh/100 ml of water. The efficiency is around 70%. The room temperature is assumed to be at 23°C [5].

Electric kettle. From empirical data, a typical electric kettle of 2400 W and 1.5 l capacity, consumes 10.4 Wh/100 ml to bring 1 l of water to its boiling point [12] and has an efficiency of about 95%.

Microwave. A 800 W microwave requires 20.7 Wh/100 g for 1 l of water to be brought from 15°C to boiling temperature, that means, an efficiency of 63% [12].

Induction and gas hobs. To best of our knowledge, no empirical evidence is available with respect to boiling water for cooking purposes. Hence, we refer to the efficiency factors reported in [11]. In particular, induction hobs are reported to be 85% efficient, whereas European regulations require gas hobs efficiency of at least 52%. Based on these efficiency factors, we calculate the energy consumption for boiling water as 11.6 Wh/100 ml and 19.0 Wh/100 ml, respectively.

Household water heater Regarding the boiler used for preheating the water, we assume a high-efficiency gas-burning boiler, characterized by an efficiency $\eta_{gb} = 0.95$, and an electric water heater with $\eta_{eh} = 0.97$