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Environmental and Economic Perspectives in the Analysis of Two Options for Hand Drying At an University Campus

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Abstract—

Environmental criteria can be part of global energy policies for the establishment of support and development actions for different technologies. Minimization of greenhouse gas emissions is a benefit to all citizens of the world, as these emissions have global scope. The objective of this study was to determine the best option for hand drying in a university campus building, from economic and environmental viewpoints, for a range of commercially available equipment. For the economic analysis, the capital and operation costs were considered along with the lifetime of the equipment. For the environmental analysis, the Life Cycle Assessment methodology was utilized. Eight options for hand drying were considered on an annual basis: five electric hand dryers and three types of paper towels. Electric hand dryers presented lower annual environmental impacts and lower annual economic costs. It is discussed that environmental impacts can and must be an active factor for the selection of one technology or another. The novelty of this study was the application of the LCA methodology to compare the carbon footprint associated with different commercially available options for hand drying in public restrooms, providing information to the consumer on which alternative is more environmentally-friendly.

Keywords— Sustainable development, Life Cycle Assessment, Hand dryer, Paper towels, Green campus.

I. INTRODUCTION

Modern society experiences a progressive transition process towards less harmful environmental behavior. This transition also includes the fact that the future energy demands will only be met if factors such as environmental impacts and energy efficiency are considered. There is a wide variety of possible energy pathways for the following decades, with different cumulative extent and intensities of environmental impacts [1].

In this way, the necessity of taking into account sustainability and environmental impacts at the time of design becomes a reality, rather than only considering the economic impacts. This necessity increases progressively due to ever-growing demands regarding the increase of sustainability [2], extending this consideration not only to design but also purchase of products. According to Baumann and Tillman [3], Life Cycle Assessment (LCA) emerges, in this context, as a comprehensive and important methodology to analyze the environmental impacts of products and services. LCA evaluates sustainability and environmental impacts associated with a product, service or process, and at the same time fulfills the necessary requirements to become a design-supporting tool.

Consideration of sustainability and environmental impacts have become fundamental for campus sustainability efforts in several countries; more specifically, carbon footprint reports have served to craft and track sustainability goals for colleges and universities [4]. Colleges and universities are progressively aspiring to make more sustainable and environmentally-sound choices [5], and can benefit from the application of the LCA methodology to evaluate policies, improve environmental performances or assess different options as demonstrated herein for hand drying options.

As mentioned by Kahler [6], estimation of environmental and financial savings achieved when reducing energy demands in one dorm room could make a difference, and these can be easily extrapolated to include the entire university residence system, establishing the potential for mitigation of climate change, for example. Comparison of alternatives can be made for retrofitting of installations [6-9] or at a design stage (case study herein presented).

Following this premise of considering sustainability for decision making, this study approaches a very common practice to decrease the amount of solid residues generated in public restrooms: substitution of paper towels by electrical hand dryers. However, the environmental impacts are not restricted to visible impacts (solid residues, contaminant emissions), also including impacts to human health, quality of ecosystems, and extraction of resources. LCA can help evaluate, from “the cradle to the grave” (extraction of raw materials, manufacture, transportation, operation, maintenance, waste scenario), products, processes, and services. The application of this methodology to different options of hand drying in campus restrooms can guarantee that the selected technology presents less associated environmental burden and, in combination with economic analysis, can help reach a balanced solution (in the case of diverging results).

There are several studies and reports on which option for hand drying is the most hygienic, economic, or efficient [9-11], however conflict of interests were identified in most publications. Another study revealed that there is no significant association between the drying method and the proliferation of bacteria [12]. Despite publicity campaigns advocating in favor of the electric hand dryer [13-14], paper towels are still widely utilized, notably in developing countries.

The necessity of reducing the environmental impacts and the consumption of energy in a significant way prevents an obvious decision to be made regarding the better option for hand drying in campus restrooms. The combined application of economic analysis with environmental assessment techniques allows for the proposition of the best option for hand drying in public restrooms, considering efficiency and sustainability issues.

Given the need for documentation and dissemination of research, studies and projects on sustainability matters at educational institutions, the objective of this manuscript is to develop economic and environmental analyses for eight options of hand drying in university restrooms: five types of electric dryers and three types of paper towels. Although the research is applied and has a Brazilian focus, in terms of the case study adopted, the work is of global scientific importance. The local dimension, even the specific university focus, is just a way in which the relevance of the science is demonstrated. Understanding the environmental effects of products, processes or services is critical to characterize sustainability, and to inform policy and regulatory decisions as well as the consumers.

II. MATERIALS AND METHODS

A. *Study Case.*

The building of the Center of Alternative and Renewable Energy (Federal University of Paraíba, Northeast Brazil) was selected for the study case. The building will host the undergraduate courses of electrical engineering and renewable energy engineering, and the graduate courses of electrical engineering and renewable energy, totalling approximately 800 students. The building is currently under construction and will include laboratories, libraries, offices and classrooms. Most of first- and second- year courses are taken at different buildings of the campus, and therefore a mean frequency of 250 persons/weekday was considered, with 50% utilizing one of the available two restrooms. During weekends, the university is closed. It was assumed that all restroom users washed and dried their hands.

After consultation with manufacturers, five electric hand dryers were selected for comparison. Table 1 presents data on the selected electric hand dryers, obtained from consultation of manufacturer specification sheets and direct information from distributors [15-19].

Table I Technical specifications of the five electric hand dryers studied

Equipment	1	2	3	4	5
Power	1800 W	1800 W	560 W	1100 W	2100 W
Drying time t_{use}	15 s	20 s	12 s	15 s	10 s
$Consumption_{use}^{*}$	0.0075 kWh	0.0094 kWh	0.0019 kWh	0.0092 kWh	0.0058 kWh
Airflow	80 l/s	70 l/s	60 l/s	52 l/s	240 l/s
Weight	3.7 kg	3 kg	12 kg	4.7 kg	4.0 kg
Cost (inc. s&h)	US$ 290	US$ 200	US$ 3400	US$ 660	US$ 480
Lifetime	6 years	6 years	7 years	6 years	6 years
Noise	n/a	70 dB	59 dB	75 dB	70 dB

* per unit hand drying process

For the paper towel scenario, three options were selected from the same manufacturer: fresh fiber, recovered fiber, and a 50%-50% combination of fresh and recovered fibers. Table 2 shows the specifications for the paper towel options.

Table III Specifications for the three paper towel options studied

Composition	Fresh fiber	Recovered fiber	50% fresh, 50% recovered
Cost of box*	US$ 30	US$ 15	US$ 20
Number of towels used **	2	4	2
Weight of box*	3.7 kg	2.5 kg	3.0 kg
Plastic dispenser		0.5 kg / US$ 21	
Waste bin		2.0 kg / US$ 10	

* 2,400 towels; ** per hand drying

The real situation of the campus building was considered: the number of regular users of the building and the amount of people utilizing the restrooms were the same for all options of hand drying.

B. *Economic Analysis.*

Traditional economic analysis considers all monetary costs involved in the selection and utilization of a specific product, throughout its lifetime. The objective of the economic analysis carried out herein is to obtain the annual costs associated with a specific option of hand drying.

The initial investment (capital cost, in US$) in a product is obtained from the manufacturer catalog, and multiplied by a simple module factor which takes into account transportation, installation, connection etc. [20-23]. This initial investment must also be multiplied by an amortization factor to obtain the investment cost. The amortization factor includes the recovery of the invested capital and its maintenance. Recovery of the initial investment considers an interest rate and the lifetime of the equipment, while maintenance of the equipment is usually given by a percentage of its initial investment (in annual terms) [24].

Operational costs are those related to the utilization of an equipment throughout its lifetime. In the case of the hand dryer, the operation costs reflect the consumption of electricity; in the case of paper towels, operation costs are the costs associated with purchasing paper towel refills.

1) Hand Dryer, For the economic analysis, ideal operation was considered – i.e., people utilized the exact time recommended by the manufacturer for each hand drying. The objective of the economic analysis was to calculate the annual cost for the electric hand dryer ($C_{annual\ dryer}$):

$$C_{annual\ hd} = C_{inv\ hd} + C_{op\ hd} \qquad (1)$$

Where $C_{inv\ hd}$ is the capital cost (initial), and $C_{op\ hd}$ is the operational cost (electricity). The capital cost can be expressed as:

$$C_{inv\ hd} = F_{am} \cdot Inv_i \qquad (2)$$

Where F_{am} is the amortization factor, and Inv_i is the initial investment, which is the purchase price of the equipment. The amortization factor (F_{am}) considers the capital recovery factor (F_{rc}) and the maintenance factor (F_m), "diluting" the initial investment throughout the lifetime of the equipment:

$$F_{am} = F_{rc} + F_m \qquad (3)$$

Considering an interest rate (i) and the lifetime of the product as (V_u), the capital recovery factor is given by:

$$\mathrm{Frc} = \frac{i \cdot (1+i)^{Vu}}{(1+i)^{Vu} - 1} \qquad (4)$$

An interest rate of 11% per year was considered herein. The maintenance factor was considered to be 2% of the purchase price of the equipment (F_m = 0.02 year-1), which was a mean value for simple, regular scheduled maintenance (*e.g.*, exchange of carbon brushes and wiring every 1,000 h of operation).

For the calculation of the annual operation cost, firstly the consumption per use (kWh) must be established. Consultation of the electricity bill provided the value of 0.1253 US$/kWh ($Cost_{kWh}$). Therefore the consumption per use ($Consumption_{use}$) was calculated as:

$$Consumption_{use} = t_{use} * Pow \qquad (5)$$

Where t_{use} is the drying time per use, and P_{ow} is the power of the equipment, according to manufacturer data (Table 1).The cost per utilization ($Cost_{use}$) is calculated as follows:

$$Cost_{use} = Consumption_{use} \cdot Cost_{kWh} \qquad (6)$$

The building presents a mean frequency of 250 persons/day, and it was considered that 50% visited the restroom facilities and washed/dried hands once (Numberuses). Considering that one year contains 365 days, of which 104 are Saturdays and Sundays, there are 261 remaining days when the campus building is open. Ten statutory holidays are also considered, when the university is closed. Annual number of hand drying operations performed is 31,375. The annual operational cost of the dryer can be summarized as:

$$C_{op\ hd} = (251 * 125 * Cost_{use}) \qquad (7)$$

Equations (1) - (7) were applied to each technology listed in Table 1.

2) Paper Towels, This step analyzes the cost of utilizing paper towels for hand drying at the restrooms of the building. No additional cleaning costs were considered in this case. The annual cost for paper towels ($C_{annual\ pt}$) is calculated as:

$$C_{annual\ pt} = C_{inv\ pt} + C_{op\ pt} \qquad (8)$$

Where is the annual cost associated with the selection of paper towels in the restrooms, $C_{inv\ pt}$ is the capital cost (initial investment in the plastic dispenser), and $C_{op\ pt}$ is the operational cost (paper towels refills). Equations (2), (3) and (4) were adapted for the paper towel plastic dispenser. The operational cost associated with utilization of paper towels is:

$$C_{op\ hd} = (251 * 125 * Cost_{use\ pt}) \qquad (9)$$

Where $Cost_{use\ pt}$ includes the number of paper towels utilized per hand drying operation ($Number_{pt}$) multiplied by the individual cost per paper towel.

C. Environmental Analysis.

The methodology followed for the environmental analysis was Life Cycle Assessment (LCA), which is a comprehensive framework that includes a high level of details, and therefore requires strict adherence to a consistent methodology, which has been established in the ISO 14000 environmental management series [25,26].

LCA was standardized by the ISO series 14040 [27,28], and consists of the following elements: definition of objectives and scope (definition of the LCA, delimits the evaluation regarding the boundaries of the system, functions and flows, necessary quality of data, technological and assessment parameters, analysis of the life cycle inventory (compilation of information on inputs and outputs for all processes of the productive system), evaluation of life cycle impact (inventory data is translated into indicators of potential impacts on the environment, human health, and availability of resources), and interpretation (the results of the previous steps are interpreted, according to the objective of the study).

There are several available methods for the assessment of environmental impacts, that utilize different environmental criteria and therefore evaluate and ponder different environmental aspects [2]. Greenhouse gas accounting has been increasingly utilized in several contexts, by industries and policy-makers, for carbon emission labeling of products or to measure the environmental performance of products, processes or services [29].

Climate changes are defined as the impact of human emissions on the radioactive forces of the atmosphere, which leads to the increase in temperature of lower layers, with adverse effects on environment and human health, among other effects. The selected characterization method (Global Warming Potential, GWP 100 [30]) was developed by the Intergovernmental Panel on Climate Change (IPCC) and considers the emission of greenhouse gases, according to emission category, aggregated by common metrics (CO_2-equivalent). The equivalent carbon dioxide is the result of the multiplication of the tonnes of greenhouse gases emitted by each global warming potential, and CO_2-equivalent expresses the potential contribution of a substance to global warming (GWP) for a time horizon of 100 years.

The program utilized to carry out LCA was SimaPro®, a software developed by the company Pré Consultants and that has been on the market since 1990 [31]. This tool is widely employed to carry out LCA due to its user-friendly interface and detailed result reports. This enables deep studies to be developed on the impacts cased and even quantify this impact in a pre-selected unit. SimaPro includes several databases for inventories, with thousands of processes, including also the most important assessment methods. All selected processes belonged to Ecoinvent version 3 [32] database to assure consistency at the time of interpretation.

The goal of the environmental analysis was to compare the life cycle environmental impact of several hand- drying methods and devices using a consistent basis. More specifically, the goal was to assess how different hand- drying methods/devices impact the environment. Despite the fact that hygiene is another aspect of interest when considering hand drying options, it was not considered herein.

Five types of electric hand dryers were considered (covering generic hands-under dryers, high speed hands-under dyers, and high speed hands-in dryer), as previously presented in Table 1. Three types of paper towels were considered, as shown in Table 2: virgin content, recovered content, and a 50%-50% combination of virgin and recovered contents. Plastic dispensers and waste bins were considered in the case of paper towels, but bin liners were not considered.

The design life of hand-drying options was set equal to six years, the lifetime of electric hand dryers. The only exception was equipment #3, which presented a design life of seven years. The plastic paper towel dispensers also presented lifetimes equal to six years. The functional unit was to provide hand drying to all the users that visited a university washroom throughout an operational year. Washroom users will only have one option at a time. Hand-drying options were compared based on the impact from the number of users over one year. This quantity of users was implemented in the SimaPro software for both electric hand dryers and paper towels to determine the amount of paper towels that would be used if the hand dryer users had chosen paper towels instead. This determines the reduction of environmental impact a user can have given that they use hand dryers or paper towels.

The environmental assessment includes all life cycle stages plus transportation between each stage. Most Brazilian technology products are produced in Southeast Brazil, and it was considered herein that the city of São Paulo concentrated manufacture of plastic dispensers, paper towels, and hand dryers. Distance between São Paulo and the location of installation (João Pessoa, Northeast Brazil) was considered as 2720 km.

Manufacture included the mining of ore or the extraction and refining of petroleum for raw materials; these materials are then transported, processed and assembled. The only energy accounted for in this stage was the energy required to manufacture dryers, dispensers or bins. The products are transported to the university campus, where the operation stage occurs. In the case of hand dryers, the operational stage considers only the electricity required to operate the equipment. For paper towels, the operational stage includes the utilization of a specific number of paper towels (pulp production, bleaching). Finally, at the end- of- life, all product types are processed by a municipal solid waste landfill.

1) Electric hand dryers, Table 3 shows the material compositions for the electric hand dryers (manufacturer data). All processes selected originated from the database of Ecoinvent [32], comprehending extraction of raw materials, energy and water consumption, concentrate inputs, transports, waste disposal, infrastructure use as well as emissions. The process selected for low-alloyed steel (Steel, low-alloyed, hot rolled) included extraction, processing and manufacturing of low-alloyed steel. The process selected for stainless steel (Steel, chromium steel 18/8, hot rolled) also included extraction, processing and manufacturing. For the PVC, the selected processes (Polyvinylchloride, emulsion polymerised; and Blow moulding) encompassed the raw material extraction, processing, and blow molding.

Table IIIII Material composition of the five electric hand dryers studied

Equipment	1	2	3	4	5
Low-alloy steel	1.5 kg	1.0 kg	0.5 kg	1.0 kg	1.5 kg
Stainless steel	1.5 kg	1.4 kg	-	2.2 kg	2.0 kg
PVC	1.0 kg	0.3 kg	10.8 kg	1.0 kg	0.7 kg
Copper	0.3 kg	0.2 kg	0.5 kg	0.3 kg	0.3 kg
Circuit	0.2 kg	0.1 kg	0.2 kg	0.2 kg	0.2 kg
Transportation	12.24 tkm	8.16 tkm	32.64 tkm	12.78 tkm	10.88 tkm

For copper, the selected process (Copper) included extraction, processing and manufacturing. A general-type circuit was included to represent motion detection (Integrated circuit, logic type) which is based on a wafer of 2% of the total packaged IC weight (2.62 g). Density of Si = 2.33 g/cm^3, wafer thickness in chip = 200 □m, including epoxy resin, nickel, lead, gold, zinc, wafer, tin, copper, silver, glass fiber reinforced plastic.

General fabrication processes were also included: general manufacturing of metal (steel and copper), and in the case of plastic, blow molding. This part of the LCA accounted for the equipment, and therefore the resulting environmental impacts must be annuitized by the lifetime of equipment to yield kg CO_2-eq/year. Annual maintenance was also included.

The next step was to add the annual consumption of electricity of the hand dryer (in the assembly stage of LCA), adding the electricity consumed from the electric grid (Ecoinvent process: Electricity, low voltage {BR}| market for | Alloc Def, S). This process considers the electricity consumed by the university campus, as provided by the electricity distribution company. The annual consumption of electricity was defined through the result of Equation (5): ($Consumption_{use}$) multiplied by the total annual number of uses ($Number_{uses}$ = 251 * 125). Spin-down and standby energy consumptions per hand drying operation were not considered herein. The electricity consumed from the electric grid included electricity inputs produced in Brazil and from imports and transformed to low voltage, the transmission network, direct emissions to air (SF6 from the insulation gas in the medium voltage level switchgear are allocated to the electricity demand on low voltage), and electricity losses during transmission [32].

The following proportions were considered for the Brazilian electricity mix (national grid): 71% hydro, 6% natural gas, 4% oil, 3% nuclear, 6% biomass (sugarcane and woody residues), and 2% wind (the remaining 8% refer to imports, which are a combination of hydro and natural gas from Argentina, Paraguay, Uruguay and Venezuela). The Brazilian electricity mix did not include leakage of insulation oil from cables and electro technical equipment (transformers, switchgear, circuit breakers) because this only happens in case of accidental release nor SF6 emissions during production and deconstruction of the switchgear, as these are accounted for in the transmission network dataset.

Assembly also included transportation from the factory to the consumer (Transport, freight, lorry 3.5-7.5 metric ton, EURO3), the unit is expressed in tonne per km (e.g., 0.0045 t multiplied by 2720 km = 12.24 tkm). This distance refers to transportation between São Paulo (location of factory, in Southeast Brazil) and João Pessoa (Northeast Brazil).

Finally, the LCA required the specification of a final waste scenario. Herein it was considered that the hand dryer was destined to the municipal solid waste landfill, after collection by truck and separation (Ecoinvent process: Municipal solid waste (waste scenario) {CH}| Treatment of municipal solid waste, landfill | Alloc Def, S).

2) Paper towels, For the plastic dispenser of paper towels, the material composition is shown in Table 4. These processes refer to the production (Polypropylene, granulate), manufacturing (Injection moulding) and transportation of the plastic dispenser (Transport, freight, lorry 3.5-7.5 metric ton) and waste bin. It was considered that under each paper towel dispenser, there was a waste bin.

Table IVV Material composition of the dispenser of paper towels and waste bin

Composition	Dispenser	Waste bin
Polypropylene	0.5 kg	2.0 kg
Injection molding	0.5 kg	2.0 kg
Transportation	1.36 tkm	5.44 tkm

The assembly comprehended three scenarios, which included the equipment (dispenser and waste bins) plus different types of paper towels utilized (100% fresh fiber, 50% fresh fiber and 50% recovered fiber, and 100% recovered fiber). Details on paper towels are shown in Table 2. Although waste bins could also be used for the disposal of other objects, impacts were fully allocated to paper towels, representing the worst- case scenario.

The processes selected included from the receipt of market pulp at the paper mill until the output of paper at the paper mill (Tissue paper production, virgin; tissue paper production, recovered; and a combination of both). The amounts of paper towels utilized throughout an operational year were: for 100% fresh fiber 213.52 kg (assuming 2 paper towels used per hand drying process, yielding 138,500 paper towels annually), 50% fresh fiber and 50% recovered fiber 193.33 kg (2 paper towels per hand drying process, yielding 138,500 paper towels annually), and 100% recovered fiber 288.55 kg (4 paper towels per hand drying process, yielding 277,000 paper towels annually). Also included was the transportation for each case, as paper towels must be delivered to the university campus located 2720 km away.

Finalization of this LCA must include the final waste scenario, which for this study was chosen to be the same scenario of the hand dryer: municipal solid waste (waste scenario).

III. RESULTS AND DISCUSSION

A) Economic analysis

1) Hand Dryer, Given the purchase cost of different electric hand dryers commercially available (Table 1), Table 5 shows the different economic parameters for these hand dryers, considering a total of 31,375 hand drying operations.

Table V Costs associated with the five different electric hand dryers

	1	2	3	4	5
Amortization factor F_{am}	0.2564	0.2564	0.2322	0.2564	0.2564
Annual capital cost C_{inv}	US$ 74.36/y	US$ 51.28/y	US$ 789.48/y	US$ 169.22/y	US$ 123.07/y
Cost per use $Cost_{use}$	US$ $9.40{\cdot}10^{-4}$	US$ $1.18{\cdot}10^{-3}$	US$ $2.38{\cdot}10^{-4}$	US$ $11.15{\cdot}10^{-4}$	US$ $7.27{\cdot}10^{-4}$
Annual operation cost C_{op}	US$ 29.49/y	US$ 37.02/y	US$ 7.47/y	US$ 34.98/y	US$ 22.81/y
Total annual cost $C_{annual\ hd}$	US$ 103.85/y	US$ 88.36/y	US$ 796.95/y	US$ 204.20/y	US$ 145.88/y

2) Paper Towels, When paper towels are utilized, it is necessary to purchase the plastic dispenser. The price of the dispenser is US$ 21 and the waste bin is US$ 10, plus US$ 20 for shipping and handling of both. Table 6 shows the different economic parameters for each type of paper towel, considering a total of 31,375 hand drying operations. Please note that the cost per use $Cost_{use\ pt}$ considers different number of paper towels utilized, depending on the type of fiber.

Table VI Costs associated with different paper towels

	Fresh fiber	50%-50% combined fiber	Recovered fiber
Amortization factor F_{am}	0.2364	0.2364	0.2364
Annual capital cost $C_{inv\ pt}$	US$ 12.06/y	US$ 12.06/y	US$ 12.06/y
Cost per use $Cost_{use\ pt}$	US$ 0.025	US$ 0.017	US$ 0.025
Annual operation cost $C_{op\ pt}$	US$ 784.38/y	US$ 533.38/y	US$ 784.38/y
Total annual cost $C_{annual\ pt}$	US$ 796.44/y	US$ 1166.23/y	US$ 796.44/y

The economic analysis of the electric hand dryer and paper towels revealed that the selection of an electric hand dryer as hand drying method entails considerably lower costs than using paper towels. This could justify the significant increase in the adoption of this method. It must be highlighted that the energy tariff utilized herein reflects the energy scenario of Brazil, where electricity is abundant, hydroelectric-originated, and economically advantageous. Of the electric hand dryers analyzed, equipment model 2 presented the best economic performance (lowest annual costs). Regarding the utilization of paper towels, 100% recovered fiber was penalized due to a higher number of paper towels utilized per hand drying operation (four), and the best economic performance was from the combination of fresh and recovered fibers (50%-50%).

B) Environmental Analysis

1) Hand Dryer, In accordance with the material composition shown in Table 3, and considerations made throughout section 2.3.1, Table 7 shows the environmental impacts associated with the LCA for each electric hand dryer considered.

Table VIILCA breakdown of environmental impacts per electric hand dryer

	1	2	3	4	5
Equipment	57.35	30.00	29.24	57.55	57.29
Operation	51.70	64.80	13.1	63.40	40.0
Maintenance	4.70	4.70	2.35	4.70	4.70
Transportation	2.12	1.42	2.43	2.22	1.88
Waste scenario	0.135	0.0747	0.177	0.135	0.128
TOTAL emissions	116.00	101.00	47.30	128.00	104.00

Figure 1 shows a Sankey diagram of the LCA for equipment 3, as it presented the lowest carbon footprint. The thickness of the ribbons indicate the contribution towards the environmental impacts. It can be verified that the assembly of the equipment accounts for 41.3% of the annual emissions, annual scheduled maintenance contributes with 3.28% (which includes recycling of electric wires), and the operational stage is responsible for 51.8% of the annual emissions. Municipal solid waste treatment corresponds to only 0.232% of annual emissions. Please note that green ribbons indicate positive environmental impacts (avoided emissions), as is the case verified within the maintenance process, which includes recycling.

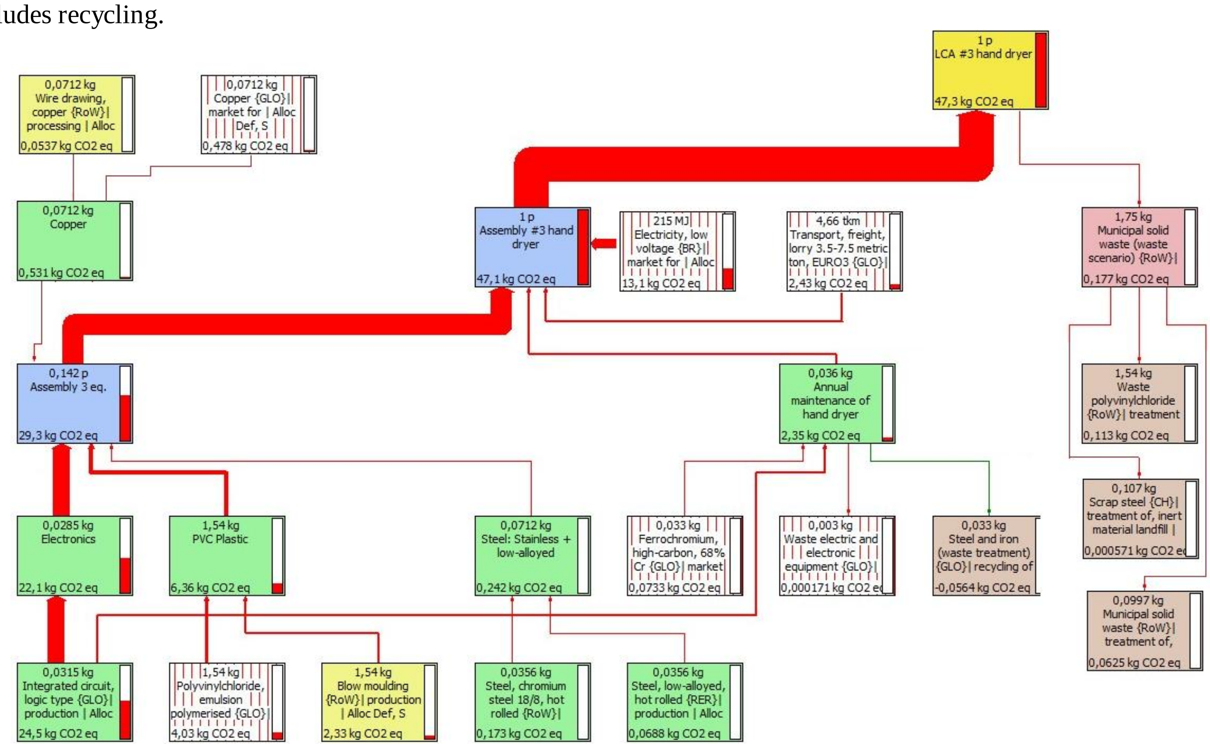

Figure 1. LCA of equipment 3, showing annual emissions for the study case.

As expected, the environmental impact of production is surpassed by the environmental impact associated with its use. This behavior has already been observed in other energy-intensive LCA studies [2,33,34], where the environmental impact of equipment could be considered negligible in comparison with the impact from energy consumption. This is usually the case in energy-intensive processes or systems.

The option for final waste scenario does not reflect any environmental conscience by part of the university campus. It was chosen as a convenient way to dispose of solid residues. When a recycling process is selected as final disposal process, each electric hand dryer is disassembled, and each component undergoes an adequate recycling process according to the constitution material. This is shown in Figure 2. Recycling contributes with -2.47 kg CO_2-eq per year, which is an avoided impact and is represented in green bars. Throughout the lifetime of the system (7 years), this can add up to approximately 17.29 kg CO_2-eq avoided.

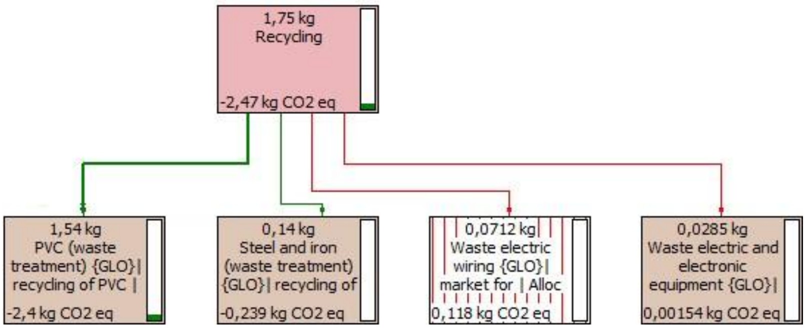

Figure 2. Final waste scenario: recycling of electric hand dryer equipment 3.

2) Paper Towels, Table 8 shows the environmental impacts associated with the LCA for each type of paper towel considered. Figure 3 shows the Sankey diagram for the utilization of recovered fiber paper towels in the washrooms of the campus building. This option was chosen because it presents that greatest carbon footprint associated with its waste scenario. It can be observed that transportation of the paper towels is responsible for 38.7% of the environmental impacts, followed by the production of recovered fiber paper towels (28.6%), and the waste scenario (32.4%, which included the municipal solid treatment of the solid residues generated). The process of producing bleached sulfite pulp and the consumption of heat were identified as the processes that most affected negatively the overall environmental impacts of the paper towels.

Table VIII LCA breakdown of environmental impacts per type of paper towel utilized

	Fresh fiber	50-50% combined fiber	Recovered fiber
Equipment	<2.00 kg CO_2-eq/y	<2.00 kg CO_2-eq/y	<2.00 kg CO_2-eq/y
Operation	427.00 kg CO_2-eq/y	228.00 kg CO_2-eq/y	137.00 kg CO_2-eq/y
Transportation	137.00 kg CO_2-eq/y	112.00 kg CO_2-eq/y	186.00 kg CO_2-eq/y
Waste scenario	115.00 kg CO_2-eq/y	93.00 kg CO_2-eq/y	155.00 kg CO_2-eq/y
TOTAL emissions	680.00 kg CO_2-eq/y	434.00 kg CO_2-eq/y	480.00 kg CO_2-eq/y

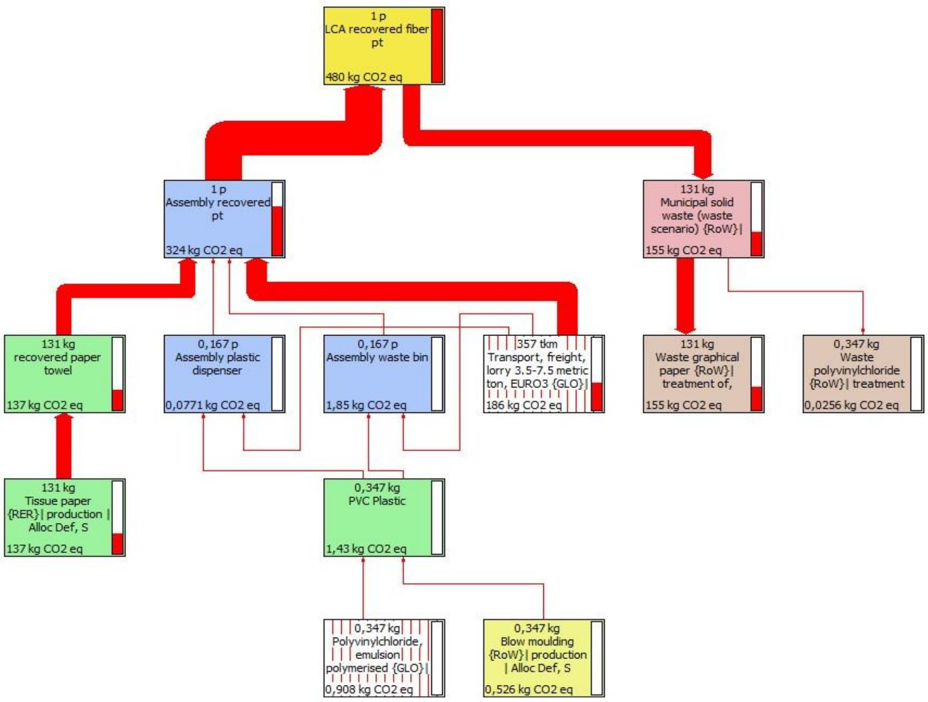

Figure 3. Sankey diagram for the utilization of recovered fiber paper towels in the campus building.

Figure 4 shows the emissions associated with recycling in the case of recovered paper. Recycling avoids the emission of 78 kg CO2-eq, yielding annual emissions of approximately 246 kg CO2-eq for the LCA. Table 9 presents a summary of economic and environmental results for the options of hand drying considered. Breakdown of the costs and environmental impacts are shown in Figure 5 and 6, respectively.

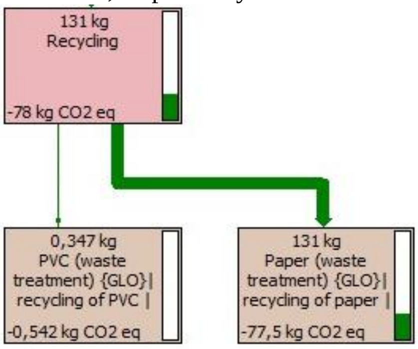

Figure 4. Emissions associated with recycling the recovered fiber paper towels, for the case study herein presented.

Table IX Summary of results for different options of hand drying method

	Annual costs, in US$/y	Annual emissions, in kg CO_2-eq/y
Electric hand dryer 1	103.85	116.00
Electric hand dryer 2	**88.36**	101.00
Electric hand dryer 3	796.95	**41.30**
Electric hand dryer 4	204.20	128.00
Electric hand dryer 5	145.88	104.00
Fresh fiber paper	796.44	680.00
50%-50% combined fiber paper	1166.23	434.00
Recovered fiber paper	796.44	480.00

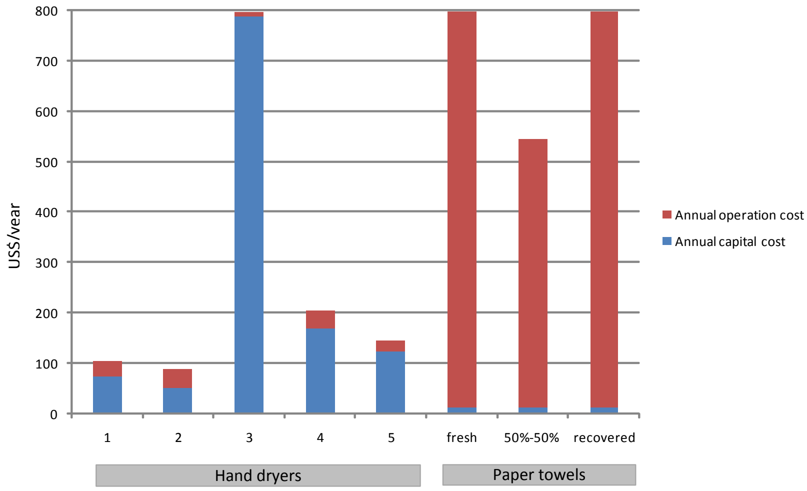

Figure 5. Comparative breakdown: costs associated with each hand drying method.

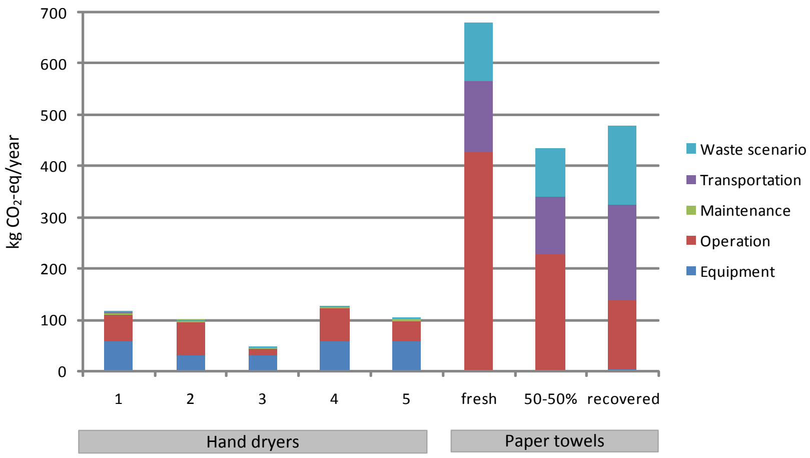

Figure 6. Comparative breakdown: environmental impacts associated with each hand drying method.

It must be highlighted that the consumption of electricity dominates the operational stage of electric hand dryers (red sections of Figure 6). A sensitivity analysis is carried out in section 3.2.3 on the carbon content of national grid electricity. In the case of the campus building herein studied, there should be two hand drying devices installed in each restroom. Under each paper towel dispenser, there is a waste bin. Table 10 presents the results of the economic and environmental analyses for the campus building.

Table X Summary of results for different options of hand drying methods at the campus building

	Annual costs, in US$/y	Annual emissions, in kg CO_2-eq/y
Electric hand dryer 1	178.21	180.31
Electric hand dryer 2	**139.58**	137.19
Electric hand dryer 3	1586.43	**81.49**
Electric hand dryer 4	373.42	192.61
Electric hand dryer 5	268.95	167.74
Fresh fiber paper	808.50	933.00
50%-50% combined fiber paper	557.50	640.00
Recovered fiber paper	808.50	823.00

The results of Tables 9 and 10 demonstrate lower annual costs and emissions for electric hand dryers. Equipment 2 presents the best compromise between cost and environmental impact, with only 25% of the cost associated with the cheapest paper towel option, and only 13% of the environmental impacts associated with the best environmental option for paper towels.

C) Environmental Sensitivity Analysis

The two factors that most affected the environmental impacts of hand dryers and paper towels, were, respectively, the energy consumed by the hand dryers during operation and the final waste scenario of paper towels.

As observed in Figure 6, the operational aspect dominated across methods of hand drying. Results could be significantly different if fossil fuel-based energy dominated national electricity generation; for example, if the aforementioned Brazilian electricity mix was 41% hydro and 34% oil with the same remaining percentages, this would yield 0.550 kg CO_2-eq/kWh consumed. Results are shown in Figure 7. No changes were implemented for paper towels (reference case).

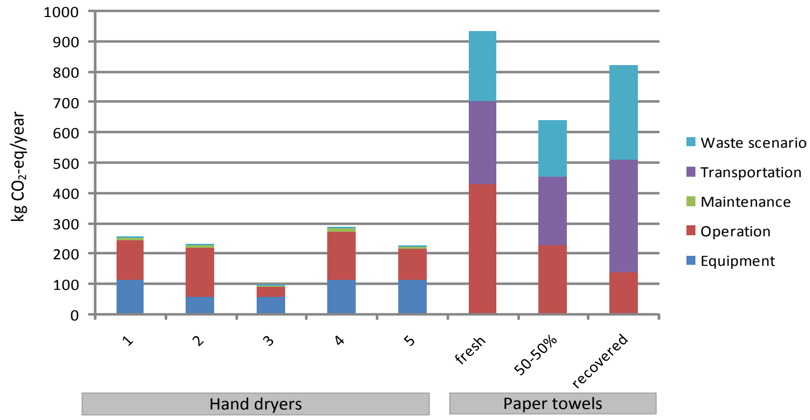

Figure 7. Sensitivity analysis: replacing 30% of hydro electricity by oil-based electricity.

Figure 8 shows that, even if 100% of Brazilian electricity was derived from coal, the environmental advantage of hand dryers would still be sufficiently significant that there would be no way of improving paper towels adequately to compete with hand dryers.

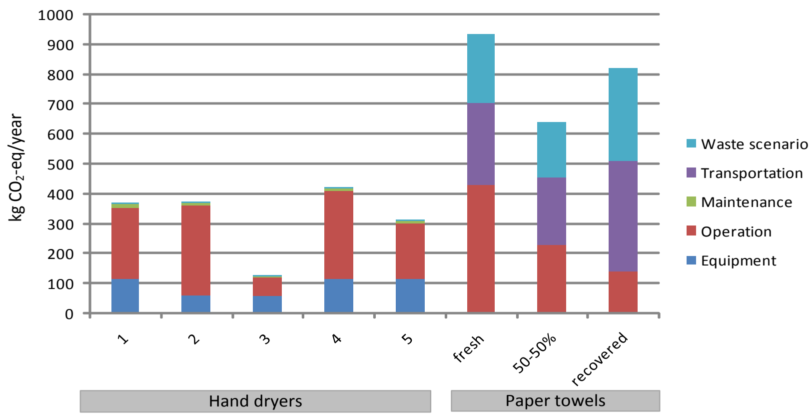

Figure 8. Sensitivity analysis: Brazilian electricity 100% coal-derived.

Regarding the final waste scenario of paper towels, even if all paper towels were recycled (with avoided emissions associated with this process), this still would not be sufficient to reduce the overall environmental impacts of this method. Figure 9 shows the consideration of recycling within the LCA of paper towels. No changes were implemented for the hand dryers (reference case).

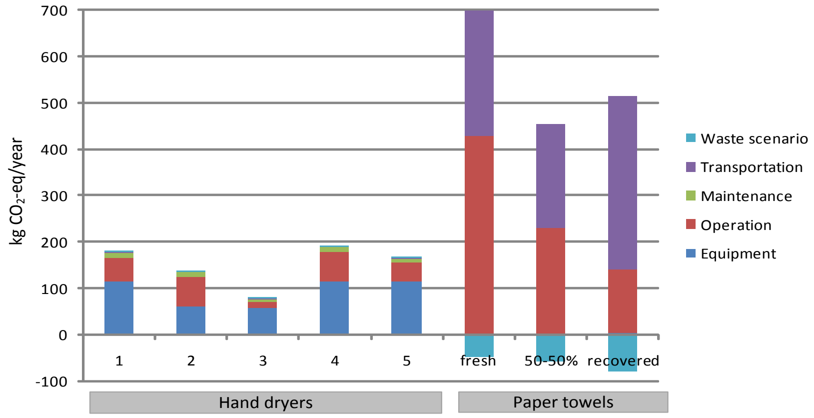

Figure 9. Sensitivity analysis: recycling as final waste scenario for paper towels.

Two Brazilian studies were found on the comparison between electric hand dryers and paper towels for hand drying. The study by [35] verified the economic viability of replacing paper towels by electric hand dryers in public restrooms, concluding that electric hand dryers were more economic for university restrooms. The study by [11] obtained better environmental performance for paper towels; however, the study considered only the energy embedded in the production of paper towels (29,876 J) vs. the energy required for hand drying with an electric dryer (32,000 J).

Most of the international studies focused on the hygienic efficacy of different hand drying methods [9,10,12,36-40]. When analyzing hand drying options, hygiene is also an aspect of interest, but it was not considered herein.

There are several articles/reports published on the specific comparison between electric hand dryers and paper towels, however conflict of interests were identified in some publications and therefore are not mentioned herein. The Public Agency Health of Canada [41] published a report on hand hygiene practices in healthcare settings, where it was mentioned that electric hand dryers could not be recommended for use in clinical areas because they are relatively slow and noisy, and hygienic efficiency was questionable, which was also the conclusion of [42-44]. However, the same study [41] mentions evidence on efficiency of three methods of hand drying (paper, cloth and electric warm air drying) in eliminating contamination and all methods of drying resulted in a further reduction of microorganisms.

A comparison of the carbon footprints for two hand drying methods, paper towels and an electric hand air dryer, was made by [45] and verified that the use of paper towels resulted in double the global warming burden when compared to the use of the hand air dryer. [46] carried out a comparative LCA of a specific hand dryer, conventional hand dryers and paper towel systems, and concluded that there was a clear advantage for high-efficiency electric hand dryers; however, similar carbon footprints were obtained for conventional hand dryers and paper towels (100% recycled).

[47] decided to carry out an LCA to compare electric hand dryers and paper towels to confirm published research that suggested that electric dryers provided more sustainable service, and finally recommended electric hand dryers to be installed in the entire campus of the University of Melbourne (Australia). An environmental sustainability assessment of a North-American university [48] concluded that there were significant CO2-eq savings in switching from paper towels to a specific hand dryer. [49] carried out an LCA of four hand dryers, cotton roll towels and two types of paper towels (recycled, virgin); the study concluded that conventional hand dryers presented higher global warming potential than paper and cotton towels. The results of a study carried out at a North American university [50] indicated that a high efficiency hand dryer reduced environmental impact and carbon footprint, and benefitted the university financially; however, user survey results indicated that user acceptance of hand dryers was low. The study by [51] concluded that the hand dryer product system was clearly the better choice with lower environmental impact in Ontario (Canada), but this cannot be generalized for all comparative LCAs between hand dryers and paper towels.

Despite the considerable resistance of consumers with respect to the electric hand dryer, it has been becoming progressively more popular and as verified herein, presented lower economic costs and lower environmental impacts for the Brazilian study case.

IV. CONCLUSIONS AND FINAL COMMENTS

The results obtained herein indicated that per dry, the use of an electric hand dryer presents lower overall carbon footprint than the utilization of paper towels. This was based on the use phase, represented by a campus building located in Northeast Brazil.

The use of electric hand dryers presented lower overall annual costs and environmental impacts. Equipment 2 presented the best compromise between cost and environmental impact, with only 25% of the cost associated with the cheapest paper towel option, and only 13% of the environmental impacts associated with the best environmental option for paper towels. However, despite these promising and encouraging results, electric hand dryers are not the preferred method for hand drying in public restrooms due to consumer rejection: many have not adapted to this technology, and many resist to even trying it.

The study presented herein reflects a Brazilian energy scenario, where most of the electricity is generated by hydropower (low-carbon technology). Countries that present an energy supply system based on thermoelectrical systems, for example, might provide different results: the environmental impact caused by the generation of electricity for the operation of the necessary hand dryers could exceed the impacts generated by the production of paper towels. This is due to the fact that this electricity would be generated by the combustion of fossil fuels, and therefore both the environmental impacts and the economic cost associated with each kWh consumed would be higher.

Small behavioral changes are progressively being implemented, focusing on sustainability, and studies such as the one herein presented help understand that even a simple gesture (hand drying) can be optimized and accomplished in an advantageous manner.

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