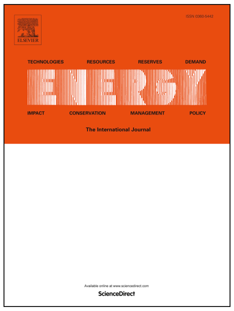


Life cycle assessment of bioenergy from lignocellulosic herbaceous biomass: The case study of *Spartina argentinensis*

Emiliano Jozami, Mele Fernando Daniel, Piastrellini Roxana, Civit Bárbara María, Feldman Susana Raquel

PII: S0360-5442(22)01118-5

DOI: https://doi.org/10.1016/j.energy.2022.124215

Reference: EGY 124215

To appear in: *Energy*

Received Date: 30 December 2021

Revised Date: 11 April 2022

Accepted Date: 5 May 2022

Please cite this article as: Jozami E, Daniel MF, Roxana P, María CivitBá, Raquel FS, Life cycle assessment of bioenergy from lignocellulosic herbaceous biomass: The case study of *Spartina argentinensis*, *Energy* (2022), doi: https://doi.org/10.1016/j.energy.2022.124215.

Statements and declarations

Funding

Field work was accomplished thanks to financial support derived from Universidad Nacional de Rosario and the Agencia Santafesina de Ciencia, Tecnología e Innovación.

Life cycle assessment of bioenergy from lignocellulosic herbaceous biomass: the case study of *Spartina argentinensis*

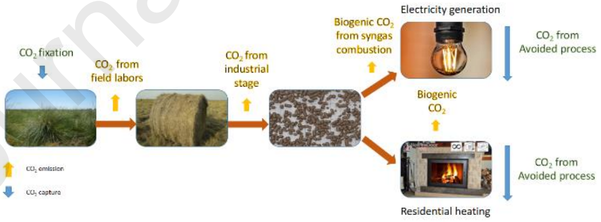
Jozami Emiliano[1*], Mele Fernando Daniel[2,4], Piastrellini Roxana[3,4], Civit Bárbara María[3,4], Feldman Susana Raquel[1,5]

[1]Facultad de Ciencias Agrarias (UNR) & Consejo de Investigaciones de la Universidad Nacional de Rosario (CIUNR).
[2]Universidad Nacional de Tucumán, Facultad de Ciencias Exactas y Tecnología (FACET), Dpto. Ing. de Procesos y Gestión Industrial. Av. Independencia 1800, (T4002BLR) S. M. de Tucumán, Tucumán
[3] Grupo CLIOPE (Energía, Ambiente y Desarrollo Sustentable), Universidad Tecnológica Nacional (UTN), Facultad Regional Mendoza (FRM) (Rodríguez 273 (5500) Mendoza.
[4] Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET)
[5] Instituto de Investigaciones en Ciencias Agrarias de Rosario.
***email: ejozami@unr.edu.ar**
CC 14 - s2125zaa Zavalla - Santa Fe Argentina

Abstract

One of the main initiatives in the context of global warming brought by the COP26 is global transition to green energy. Bioenergetic utilization of unharnessed renewable resources, such as native rangeland frequently subjected to fires, is a promising alternative to displace fossil fuels. *Spartina argentinensis* is a native perennial grass that develops in a depressed area of 33,000 km^2 in Santa Fe province (Argentine) named “Los Bajos Submeridionales”. A life cycle assessment (LCA) was performed analyzing the bioenergetic utilization of *S. argentinensis*. Two alternative scenarios (AS) were assessed and compared to their business as usual (BAU) counterparts: pellets for i) gasification to deliver electricity to the grid (ASp), contrasted to the Argentinean energy mix (BAUp) and ii) residential heating (ASh) contrasted to natural gas heating (BAUh). Carbon Balance of both AS were negative noticeably lower than BAU and the energy balance was promising considering that the produced energy was higher than that required along the complete system assessed. This is the first LCA of bioenergy from *S. argentinensis* and according to the results, this biomass resource could collaborate remarkably in climate change mitigation, which is auspicious considering the vast region occupied by this grass and others with similar characteristics.

Graphical abstract



Highlights

- ***Spartina argentinensis* can be pelletized without need of an additive**
- **Pellets can produce syngas for CHP or can be burnt for residential heat**
- **Renewable energies assessed produce significant lower GHG than fossil counterparts**
- **Renewable scenarios present high Energy Return on Investment**

Statement of Novelty

Against the backdrop of growing global demand for clean energies, this paper assesses potential bioenergetic uses for *Spartina argentinensis*, an unharnessed renewable resource frequently burned in the fields. A Life Cycle Assessment (LCA) study is performed to compare the environmental performance of *S. argentinensis* with that of the fossil energy to be replaced. Results are remarkably auspicious in terms of reduction of greenhouse gas emissions and energy balance. This is the first LCA of *S. argentinensis*, a species similar to many other constituent grasses of subtropical and tropical rangelands. This research will enable policy makers to make informed decisions to stimulate the investments necessary to exploit such a valuable resource.

1 Introduction

Fossil fuels consumption has grown steadily since the industrial revolution and, consequently, its combustion has led to an unprecedented increase in the atmospheric concentration of carbon dioxide, methane, and nitrous oxides among other greenhouse gases (GHG). Such an increase in GHG is considered to be the driving force of global warming [1].

The energy sector accounts for two-thirds of global GHG emissions [2]. Thus, renewable energy will probably play a key role as an alternative to fossil fuels, contributing to global warming mitigation in the near future [3]. Renewable energy production has grown over the last decades stimulated by legislation intended to increase its production, to face high volatility of the fossil fuel prices, and to mitigate the climate change consequences [4–7].

The main contributors to renewable energies are traditional biofuels such as bioethanol and biodiesel mostly used for the transportation sector [8]. Most of these biofuels are derived from edible feedstock such as corn, sugarcane, rapeseed, and soybean among others [9]. Such food-derived biofuels are named first generation biofuels (1G) and the sustainability of their production has aroused large discussions among the population in general and scientists in particular [10–12]. Moreover, the use of such a feedstock is far from becoming a solution to the energy sector: if all cereal crops were totally derived to 1G bioethanol production (obviously an extreme and not a viable scenario), less than 60% of global gasoline energy demand would be satisfied [13].

Unlike 1G, second generation biofuels (2G) are obtained mainly from cellulose present in non-edible renewable sources (so-called energy crops, stubble, grasses, short rotation coppice, and pruning waste among others). Cellulose is the most abundant organic compound on Earth [14], hence many investigations sustain that these biofuels will cover a significant share of energy offered by 2030 [15].

Biomass conversion processes can be divided into Physio-chemical, biochemical and thermochemical conversion technologies [16]. Among the thermochemical processes transforming biomass into biofuels, gasification involves a complex set of reactions operating from moderate to high temperatures (600-1200 °C) that transforms biomass into a low energy "poor" gas (syngas) suitable for being combusted for electricity generation. Both the reactions extent and the syngas composition strongly depend on the raw material features and the technology used. Syngas can also be used to produce heat through cogeneration in a combined heat and power (CHP) plant with 15-35% and 55% power and heat efficiency, respectively [16,17].

Another possible use, after catalytic methanation, is to produce synthetic natural gas [18]. In contrast to wood biomass, most grasses possess a high content of low melting point ashes which makes them unsuitable for traditional gasification technologies. However, some gasifiers can operate at lower temperatures to avoid slagging. Such reduction of operational temperature can bring problems with the concentration of tars (a complex and varied mixture of condensable hydrocarbons) in the syngas which requires additional cleaning steps [19]. An Argentine company (Industrias Savini SRL®) has recently developed a gasifier, in association with the Department of Chemical, Material, Environmental Engineering of the University of Rome “La Sapienza”, which can operate at lower temperatures and thus gasify biomass presenting low melting point ashes.

Another way of employing lignocellulosic biomass for energy purposes is as pellets for domiciliary combustion in pellet stoves designed for residential heating, being a sustainable alternative to traditional firewood [20]. Even though most research on biomass-based pellets has been done assessing wood pellets, a lot of work has been performed recently evaluating herbaceous pellets production [21–23]. Herbaceous biomass presents very low bulk density, hence, its densification is mandatory to avoid technical and economical logistic issues.

Rangelands, including arid and semiarid areas [24], occupy two-thirds of Argentina. *Spartina argentinensis* Parodi (=*Sporobolus spartinus* (Trin.) P.M. Peterson & Saarela) is a C4 perennial grass dominant in a large depressed zone named “Bajos Submeridionales”, an area of *circa* 30,000 km^2 extending over three provinces of Argentina: (i) the central and northern region of Santa Fe, (ii) the south of Chaco, and (iii) the east of Santiago del Estero. This area is sparsely populated and presents a very low economic activity where most farmers are cattle raisers with low productivity since *S. argentinensis* presents low digestibility. Fire is commonly used to burn senescent biomass to stimulate the growth of new and tenderer leaves of *S. argentinensis.* This management releases carbon dioxide into the atmosphere without neither an energetic nor an economic utilization of the biomass. Moreover, this fire generates multiple health issues to the population near the burnt rangelands, among which, particulate matter emissions stand out. *Camponotus punctulatus* anthills are frequent in these communities and can reach up to 1 m in height. They do not disturb livestock breeding, but must be dismantled before biomass harvesting.

Local researchers studied thoroughly *S. argentinensis* communities [25–27]. The effect of fire has also been deeply-analyzed observing that after such disturbance, the emergence of other species present in the seed bank increases the diversity of the community for a short period after which *S. argentinensis* becomes dominant again [27–29]. The effect of clipping biomass did not differ from the effect of fire, under greenhouse and field experimental conditions [27,28].

This proposal does not pursue altering the landscape and diversity of these rangelands, but to integrate its actual cattle raising main activity with bioenergy production, replacing fire with harvest, while leaving enough time for recovery assuring resource sustainability. This activity would allow for clean energy production with minimal anthropic intervention in the ecosystem. This is the first LCA of *S. argentinensis* derived bioenergy, hence it will help policy makers to stimulate sustainable processes of clean energy production while reducing particulate matter caused by rangeland burning within this vast region. The proposal would also generate economic profits to service providers within this underdeveloped region.

The aim of this research is to highlight the environmental benefits of replacing fossil fuel derived energy by energy obtained from this biomass for both residential heating and for electricity production. This is expected to be accomplished by assessing the environmental impacts associated to two uses of *S. argentinensis*: bioelectricity generation in a CHP plant, and residential heating through pellets combustion. Life Cycle thinking criteria is used to compare the proposed bioenergy systems with their fossil actual counterparts mostly employed in Argentina. Human health would also be improved by this proposal considering the decrease of particulate matter derived from rangeland fires. Hence, these results can be helpful for policy makers on decisions concerning the sustainability of rangelands management.

2 Materials and Methods

The product system was modeled using primary information when possible and bibliography data for those items for which local information was not available. Data for the inventory was collected and processed in a Microsoft Excel spreadsheet and SimaPro 9.0.0.35 Faculty [30]. Life cycle assessment (LCA) was accomplished following the guidance of the International Organization for Standardization 14040 series for LCA [31,32]. The LCA was accomplished with a cradle-to-grave perspective, that is, from the raw material extraction to the final disposal of the product. The four phases of the LCA are described in next subsections.

2.1 Goal and scope of the study

The goal of this study was to assess the environmental impacts of two alternative scenarios (AS) using biomass of *S. argentinensis*: (i) production of power (ASp) with three sub-scenarios according to the fraction of heat from syngas combustion exploited (ASp_0, ASp_{50} and ASp_{90}, for 0%, 50%, and 90%, respectively) and; (ii) pellets for domiciliary heating (ASh), to compare them with the business as usual scenarios (b). BAUp and BAUh stand for electricity of the Argentinean energy mix and the residential heating with natural gas stoves, respectively. Since the driving force of biofuels is climate change mitigation and energy security, the following impact categories were assessed: (i) climate change using GWP (with a time horizon of 100 years) as an indicator, and (ii) energy use with cumulative energy demand (CED) and energy return on investment (EROI) as indicators.

The energy flow of ASp_{90} and ASh are shown in Fig. 1 and 2 respectively. Both figures were performed using a Sankey Diagram generator [33]. Lower heating value (LHV) was calculated using the equation proposed by Golato et al. (2017) [34]:

$$LHV = HHV.(1 - w) - 2512[9.H(1 - cz).(1 - w) + w]$$

Where *w* is the biomass moisture content, *cz* is the ash content, and *H* is the ash free hydrogen content.

HHV was obtained with a bomb calorimeter (IKA C5000). The moisture content was measured drying the biomass at 105 °C until constant weight. The elemental Hydrogen content was obtained from Rada Arias et al. (2020) [14]. ASp_0 and ASp_{50} are similar to Fig. 1 with the only difference at “harnessed heat” which is null and 1.13 MWh respectively.

Fig. 3 and 4 depict the system boundaries of both product systems modeled in this study. The first one represents the electricity generation system whose functional unit (FU) is to deliver 1.0 MWh of electricity to the power grid. This electricity comes from the combustion of syngas obtained *via* gasification of *S. argentinensis.* Gasification was accomplished in a 250 kW gasifier that belong to “Industrias Savini SRL®”. For reasons of confidentiality, no further information is provided regarding the gasifier design.

Fig. 4 corresponds to domiciliary heating systems in which the FU is to deliver 1 MJ of useful thermal energy for residential heating. Co-products environmental burdens were accounted using the system expansion approach by subtracting the emissions of the avoided products to the system product assessed. The AS replaces fossil fuels of BAU scenarios with field labors and industrial processes needed for achieving the FU. ASh scenario avoids the emissions of non-biogenic GHG while ASp avoid these emissions in addition to those avoided by heating with biochar and syngas cogeneration instead of using natural gas at the industrial sector.

2.2 Inventory analysis

Field stage data was obtained from a rangeland where 14,000 m^2 were harvested. Biomass availability was circa 700 g of dry matter per m^2. Harvest efficiency was 48% thus 337 g of dry matter were obtained per m^2. Tables 1 and 2 show the processes involved in ASp and ASh respectively, while Table 3 shows the avoided processes for each AS. Land occupation was calculated according the biomass yield mentioned above. The power required for the pelletizing facility was obtained by the National Institute of Industrial Technology (INTI) were *S. argentinensis* pellets have been obtained.

For field labors, the diesel consumption was measured and an equivalent quantity was used from the dataset named "machine operation, diesel, >= 74.57 kW, high load factor" [35]. Both alternative scenario systems included biomass transportation to processing facilities located 30 km away, using the process "Transport, truck >20t, EURO1, 100%LF, default/GLO Mass" [36,37].

The electricity demand of the gasification facility was considered to be self-supplied. Therefore, to fullfill the FU, a surplus of power equivalent to 0.22 MWh needs to be produced. This was accomplished by a 1.22 factor multiplied to every process involved in this system product. Thus, processes that demand electricity did not need to be further considered.

In the alternative scenarios, the field stage was considered integrated with livestock production systems where fire was replaced by harvest and thus, GHG emissions of non-biogenic carbon (i.e: methane and nitrous oxide) from rangeland burning were avoided. Such emissions were accounted using the IPCC emission factors [40].

2.3 Characterization model and impact categories

For the impact category "Climate Change", the indicator used was global warming potential according to the ReCiPe method (Hierarchist) at midpoint level [42]. For the impact category "Energy Use", the indicator Cumulative Energy Demand (LHV) V1.00" [43] method was applied and the EROI [44] was calculated.

2.4 Interpretation

The results of the impact categories assessed were contrasted for each scenario against their BAU counterparts to elucidate whether the AS resulted less aggressive with the environment or not. Furthermore, the impact indicators were broken down in different processes to identify the main hotspots contributing to each impact category.

3 Results

3.1 Global warming potential

The GWP of the electricity production system is depicted in Fig. 5 where differences can be appreciated among scenarios. All alternative scenarios have negative CO_{2eq} emissions when avoided processes are considered even under the most pessimistic one, ASp_0. The main reason for this is the avoided emissions from rangeland burning which accounts for 281 kg of CO_{2eq} and heat from syngas combustion with figures of 311 and 560 kg of CO_{2eq} for ASp_{50} and ASp_{90}, respectively. As expected, biochar has a minor contribution in the alternative scenario considering its mass represents less than 10% of the biomass. Syngas combustion is the main contributor to emissions from the alternative scenarios followed by the field labors. However, ASp emissions are less than a third part of those produced by the BAUp scenario, which refers to the Argentine energy mix.

Fig. 6 shows the GWP results from the residential heating scenarios. In line with previous figures, AS presents lower emissions of CO_{2eq}. For this system, the BAUh scenario emitted six-fold the emissions than the ASh counterpart (without considering the avoided emissions). For ASh, the industrial stage was the main contributor to GWP. When considering system boundaries expansion, ASh'CO_{2eq} emissions are approximately neutral. The breakdown of the industrial stage can be appreciated in Fig. 7. The main contributor of CO_2 in the industrial stage is pelletizing.

3.2 Energy use

3.2.1 Cumulative energy demand

Energy output and inputs for the scenarios modeled for power production are depicted in Fig. 8. For all of them, the FU of 1 MWh can be appreciated by the blue color in each bar. Additional energy outputs are obtained by biochar and syngas heat in ASp. As expected, the energy input of the Argentine energy mix is higher than its renewable energy counterpart.

Fig. 9 highlights the energy balance of the residential heating systems. As no co-products are produced in ASh, no additional energy output is produced here. The energy demand for BAUh is over 5 fold than that of ASh.

3.2.2 Energy return on investment

Both BAU scenarios presented net energy losses which means that for a given quantity of energy output, there are higher energy inputs along the life cycle of the production process. The energy returns on investment (EROI) of both systems evaluated can be appreciated in Fig. 10 and 11. The renewable energy scenarios resulted promising with an EROI ranging from 6 to more than 15 for the ASp and close to 4 for ASh. This implies that for ASh, for every MJ of energy invested, almost 4 MJ can be produced employing *S. argentinensis* as feedstock. These figures are promising when compared with the fossil-based BAU scenarios where, for each MJ of energy produced, over 1 and 3 MJ are invested for the BAUh and BAUp respectively.

4 Discussion

Although gasification is a long-standing method, it has recently gained much interest due to its energy efficiency with a wide range of materials [45–47]. Samsom et al. [45] claimed that even though there are some technological barriers regarding gasification of C4 grasses, such as low energy density and high amounts of chorine that can hinder their use for bioenergy, there are many possible solutions to overcome them. Furthermore, this type of biomass presents many advantages, as they thrive in agricultural marginal soils and have very low growing costs.

However, there is not much information on the use of natural grassland species as raw material for gasification and even less with *Spartina* species. Moutsoglou [49] simulated the gasification of *Panicum virgatum* and *S. pectinata* concluding that the latter would yield a syngas with a higher calorific value than the former one. Emery et al. [50] modeled biogasoline obtained from prairie cordgrass (*Spartina pectinata* L.) with up to 80% reduction of GHG. Jozami et al. [51] stated that 96% of the energy demand of gasoline of the province of Santa Fe could be met if using biomass available in one-third of the area of *S. argentinensis* communities for bioethanol. A techno-economic assessment of *S. argentinensis* biomass gasification was accomplished as well [17]. Other C4 rangelands often burned [52,53], could also be considered for bioenergy and cattle raising in future research. Tri-generation technologies have also been evaluated in the genus *Spartina* to produce electricity, heat and gas [54] although this studies do not considered the enviromental assessment.

Many authors sustain that bioenergy use is even compatible with rangelands conservation. Jungers et al. [55] found that annual harvests at the end of the summer did not affect biodiversity and are suitable for bioenergy, pointing out the relevance of complementing conservation with energy use. Sosa et al. [56] evaluated different frequencies of biomass clipping for bioenergy and found that neither the arthropods nor the plant communities were affected by biomass clipping and removal when comparing it with no clipped plots.

A quarter of the global soil organic carbon (SOC) pool is located in grasslands and savannas [57]. Thus, much research has been focused on studying the effects of grassland management in SOC [58–61]. Rangeland burning effects on SOC and carbon balances have also been largely studied with different results. Knicker [62] reviewed researches about this topic showing that under some grassland burning scenarios, SOC increased whereas in other cases it decreased. These contrasting results can be expected considering that SOC can be modified by different causes, and rangelands fires can vary in intensity and duration as well as the condition of soil conductivity. Soil erosion simulated after fire, increased according to Johansen et al. [63]. Figures of post-fire soil erosion simulations, resulted higher in forests than in grasslands.

When considering the whole carbon balance, the carbon emissions by combustion, and the higher carbon mineralization rates after burning, Zhao et al. [64] found that "fires increased CO_2 emissions to the atmosphere not only during the combustion process, but also for an extended post-burning period" when compared to unburned northeastern China wetlands.

Previous research found that total carbon stocks were over 60% higher in dry season enclosed rangelands than in those managed with prescribed fires [65]. This proposal is in the middle term between a full biomass harvest and an enclosure, as half of the total biomass would remain at the ground due to the low harvest efficiency of *S. argentinensis* rangelands (*circa* 50%). Hence, it could be hypothesized that SOC could increase in a harvest vs. burning experiment. More research should be done to test this hypothesis.

In this research, biochar energetic utilization was considered following LCA similar to the one realized by Jens et al [66]. Other potential uses for biochar should be assessed in future research like activated carbon for adsorption applications, soil amendment and carbon sequestration among other potential uses [67].

In both types of energy assessed in this research, the environmental impact (measured through GWP and CE) resulted lower than its fossil counterpart. These results are consistent with a review that addressed 58 papers assessing LCA bioenergy production [68]. However, the fact of considering biomass fire as an avoided process in this research reduced the amount of CO_2eq emissions to approximately neutral and negative figures for ASh and ASp respectively. This proposal does not require a modification of land use, making it more attractive than other bioenergy alternatives.

Processing satellite images, Pinilla Vargas [69] found that the areas where the *S. argentinensis* communities grow, presented a high frequency of burning. More than 100 foci per year were observed during the period 2000-2014 by assessing pixels of 0.5° x 0.5° (approximately 3000 km^2). Verón et al. [70] analyzed annually burnt biomass from agricultural and non-agricultural areas and calculated how much electricity could be potentially obtained with nowadays technologies. It is interesting to note that, if burnt biomass from Argentine non-agricultural land would be derived to produce electricity, the total country power demand could be met.

5 Conclusions

Spartina argentinensis rangelands used for cattle raising could improve its productivity if frequent fires were replaced by harvest for bioenergy purposes. Such proposal would not only elevate the agronomic profitability due to the new demand generated to an underused product but also would make these ecosystems more sustainable by increasing soil organic carbon (produced by an increase of remaining biomass after harvest, when comparing it with fires), and avoiding biomass burning which generates a sudden CO_2 (yet biogenic) and particulate matter emissions to air, among other compounds emissions. Avoiding particulate matter emissions by fires would prevent many health issues to nearby residents.

This is the first research performed in Argentine assessing bioenergy from *S. argentinensis*, an untapped biomass resource, with an LCA thinking criteria. Several advantages, when comparing this proposal with the business as usual scenario, are highlighted regarding the outstanding environmental performance of *S. argentinensis* bioenergy for both, residential heat and bioelectricity alternative scenarios. The main advantages are (i) lower GHG emissions and energy use, (ii) the decrease of rangeland fires and its particulate matter emissions, and (iii) the fact that no land use change would be necessary.

Considering that machinery required for the proposal is mostly available (only some design of machinery is needed to dismantle anthills), there are no difficult barriers to overcome. Furthermore, the vast region potentially used for this proposal would result beneficed for new requirements of field services that would facilitate growth and development of an unpopulated region located at the north of Santa Fe province, Argentina.

The objective of this research was accomplished as it was demonstrated that sustainable energy can be produced from *S. argentinensis* allowing a reduction of both atmospheric GHG and abiotic resource depletion. This research is expected to be useful for policy makers, research institutions and private enterprises interested in bioenergy which is a steadily growing sector in Argentina and worldwide. More research should be carried out in order to assess long term effect of *S. argentinensis* harvest in soil carbon as this could modify this LCA result regarding the climate change impact category.

Statements and declarations

Funding

Field work was accomplished thanks to financial support derived from Universidad Nacional de Rosario and the Agencia Santafesina de Ciencia, Tecnología e Innovación.

Data Availability

The datasets generated and analyzed during the current study are not publicly available as part of the data will be published in the main author thesis, but are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare no competing interests.

Author Contributions

The present research was accomplished in the context of the first author (Emiliano Jozami) doctoral thesis. Dr. Susana Feldman is the director and Dr. Bárbara Civit is the co-director and both collaborated with the writing of the paper as well as guiding Emiliano along the process of the LCA. Dr. Fernando Mele collaborated in grammar of the paper and with figures and tables. Roxana Piastrellini helped with the writing of the paper and collaborated with the data needed for the software Simapro.

References

[1] IPCC. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva Switzerland. Cambridge/New York: Cambridge University Press; 2014.

[2] Rosenzweig RH. Global Climate Change Policy and Carbon Markets. London: Palgrave Macmillan UK; 2016. https://doi.org/10.1057/978-1-137-56051-3.

[3] Neupane B, Halog A, Dhungel S. Attributional life cycle assessment of woodchips for bioethanol production. Journal of Cleaner Production 2011;19:733-41. https://doi.org/10.1016/j.jclepro.2010.12.002.

[4] Guo M, Song W, Buhain J. Bioenergy and biofuels: History, status, and perspective. Renewable and Sustainable Energy Reviews 2015;42:712-25. https://doi.org/10.1016/j.rser.2014.10.013.

[5] Balat M. An overview of biofuels and policies in the European union. Energy Sources Part B-Economics Planning Policy 2007;2:167-81. https://doi.org/10.1080/15567240500402701.

[6] Scarlat N, Dallemand JF, Monforti-Ferrario F, Nita V. The role of biomass and bioenergy in a future bioeconomy: Policies and facts. Environmental Development 2015;15:3-34. https://doi.org/10.1016/j.envdev.2015.03.006.

[7] Mathews J a., Goldsztein H. Capturing latecomer advantages in the adoption of biofuels: The case of Argentina. Energy Policy 2009;37:326-37. https://doi.org/10.1016/j.enpol.2008.07.022.

[8] Ritchie H, Roser M. Renewable Energy 2020. https://ourworldindata.org/renewable-energy.

[9] Bracco S. The Economics of Biofuels: The Impact of EU Bioenergy Policy on Agricultural Markets and Land Grabbing in Africa. Abingdon, Oxon ; New York, NY : Routledge, 2016.: Routledge; 2016. https://doi.org/10.4324/9781315621111.

[10] Popp J, Lakner Z, Harangi-Rákos M, Fári M. The effect of bioenergy expansion: Food, energy, and environment. Renewable and Sustainable Energy Reviews 2014;32:559-78. https://doi.org/10.1016/j.rser.2014.01.056.

[11] Tilman D, Socolow R, Foley JA, Hill J, Larson E, Lynd L, et al. Beneficial Biofuels—The Food, Energy, and Environment Trilemma. Science (80-) 2009;325:270-1. https://doi.org/10.1126/science.1177970.

[12] Maltsoglou I, Felix E, Kojakovic A, Rincon LE, Branca G, Valle S, et al. Combining bioenergy and food security : An approach and rapid appraisal to guide bioenergy policy formulation. Biomass and Bioenergy 2015:1-16. https://doi.org/10.1016/j.biombioe.2015.02.007.

[13] Rajagopal D, Sexton SE, Roland-Holst D, Zilberman D. Challenge of biofuel: filling the tank without emptying the stomach? Environmental Research Letters 2007;2:044004. https://doi.org/10.1088/1748-9326/2/4/044004.

[14] Rada Arias E, Bertero M, Jozami E, Feldman SR, Falco M, Sedran U. Pyrolytic conversion of perennial grasses and woody shrubs to energy and chemicals. SN Applied Sciences 2020;2:116. https://doi.org/10.1007/s42452-019-1911-4.

[15] Alizadeh R, Lund PD, Soltanisehat L. Outlook on biofuels in future studies: A systematic literature review. Renewable and Sustainable Energy Reviews 2020;134. https://doi.org/10.1016/j.rser.2020.110326.

[16] Adams P, Bridgwater T, Lea-Langton A, Ross A, Watson I. Biomass Conversion Technologies. Greenhouse Gases Balances of Bioenergy Systems, Elsevier; 2018, p. 107-39. https://doi.org/10.1016/B978-0-08-101036-5.00008-2.

[17] Jozami E, Porstmann JC, Shocron A, Feldman SR. Techno-economic Assessment of Biomass Gasification of *Spartina argentinensis*. Agrociencia-Uruguay 2017.

[18] Steubing B, Zah R, Ludwig C. Life cycle assessment of SNG from wood for heating, electricity, and transportation. Biomass and Bioenergy 2011;35:2950-60. https://doi.org/10.1016/j.biombioe.2011.03.036.

[19] Coulson M, Dahl J, Gansekoele E, Bridgwater a. V, Obernberger I, van de Beld L. Ash Characteristics of Perennial Energy Crops and Their Influence on Thermal. 2nd World Conference Biomass Energy, Industry Climate Protection 2004:359-62.

[20] Pa A, Bi XT, Sokhansanj S. Evaluation of wood pellet application for residential heating in British Columbia based on a streamlined life cycle analysis. Biomass and Bioenergy 2013;49:109-22. https://doi.org/10.1016/j.biombioe.2012.11.009.

[21] Cherney JH, Verma VK. Grass pellet Quality Index: A tool to evaluate suitability of grass pellets for small scale combustion systems. Appl Energy 2013;103:679-84. https://doi.org/10.1016/j.apenergy.2012.10.050.

[22] Jannasch R, Samson R, de Maio A, Adams T, Ho Lem C. Changing the energy climate: clean and green heat from grass biofuel pellets. Climate Change 2 Canadian Technology Development Conference, 2001.

[23] Roy MM, Dutta A, Corscadden K. An experimental study of combustion and emissions of biomass pellets in a prototype pellet furnace. Appl Energy 2013;108:298-307. https://doi.org/10.1016/j.apenergy.2013.03.044.

[24] Fernández O, Busso C. Arid and semi-arid rangelands: two thirds of Argentina 1999. (pp. 41-60). Reykjavíc, Iceland: Agricultural Research Institute.

[25] Lewis JP, Collantes MB, Pire EF, Carnevale NJ, Boccanelli SI, Stofella SL, et al. Floristic groups and plant communities of southeastern Santa Fe, Argentina. Vegetatio 1985. https://doi.org/10.1007/BF00040350.

[26] Lewis JP, Pire EF, Prado DE, Stofella SL, Franceschi EA, Carnevale NJ. Plant communities and phytogeographical position of a large depression in the Great Chaco, Argentina. Vegetatio 1990;86:25-38. https://doi.org/10.1007/BF00045133.

[27] Feldman SR, Lewis JP. Effects of fire on the structure and diversity of a *Spartina argentinensis* tall grassland. Applied Vegetation Science 2005;8:77-84. https://doi.org/10.1111/j.1654-109X.2005.tb00631.x.

[28] Feldman SR, Bisaro V, Lewis JP. Photosynthetic and growth responses to fire of the subtropical-temperate grass, *Spartina argentinensis* Parodi. Flora 2004;199:491-9. https://doi.org/10.1078/0367-2530-00177.

[29] Feldman SR, Lewis JP. Demographic responses to fire of *Spartina argentinensis* in temporary flooded grassland of Argentina. Wetlands 2007;27:785-93. https://doi.org/10.1672/0277-5212(2007)27[785:DRTFOS]2.0.CO.

[30] PRé sustainability B.V. SimaPro 9.0.0.35 2019. www.pre-sustainability.com/software.

[31] ISO. 14040: Environmental management — Life cycle assessment — Principles and framework. 2006.

[32] ISO. 14044: Environmental Management – Life Cycle Assessment – Requirements and Guidelines. 2006.

[33] Services Acquire Procurement. Sankey diagram generator s. f. http://sankey-diagram-generator.acquireprocure.com.

[34] Golato M, Feijóo E, Franck Colombres F, Paz D, Cárdenas G. Estudio preliminar del aprovechamiento de los residuos agrícolas de cosecha de la caña de azúcar como combustible adicional para calderas bagaceras de Tucumán (Argentina). Revista Industrial y Agrícola Tucumán 2017;94:21-31.

[35] Blonk Agri Footprint BV. Agri - footprint 2.0 - Part 1: Methodology and basic principles. 2015.

[36] Blonk Agri Footprint BV. Agri - footprint 2.0 - Part 2: Description of data. 2015.

[37] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. International Journal Life Cycle Assessment 2016;21:1218-30. https://doi.org/10.1007/s11367-016-1087-8.

[38] Huang YF, Syu FS, Chiueh P Te, Lo SL. Life cycle assessment of biochar cofiring with coal. Bioresource Technology 2013;131:166-71. https://doi.org/10.1016/j.biortech.2012.12.123.

[39] Brewer CE, Brown RC, Laird DA. Biochar characterization and engineering. Graduate Teses and Dissertations 2012:12284. https://doi.org/12284.

[40] Gómez DR, Watterson JD, Americano BB, Ha C, Marland G, Matsika E, et al. Chapter 2:

Stationary Combustion. IPCC Guidelines National Greenhouse Gas Inventories, Geneva, Switzerland: 2016.

[41] National Renewable Energy Laboratory. U.S. Life Cycle Inventory Database 2012. https://www.lcacommons.gov/nrel/search (accessed 19.11.2021).

[42] Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, et al. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. International Journal Life Cycle Assessment 2017;22:138-47. https://doi.org/10.1007/s11367-016-1246-y.

[43] Weidema BP, Bauer C, Hischier R, Mutel CL, Nemecek T, Reinhard J, et al. Overview and methodology: Data quality guideline for the ecoinvent database version 3. 2013.

[44] Arvidsson R, Svanström M. A framework for energy use indicators and their reporting in life cycle assessment. Integrated Environmental Assessment and Management 2016;12:429-36. https://doi.org/10.1002/ieam.1735.

[45] Prasad L, Subbarao PMV, Subrahmanyam JP. Experimental investigation on gasification characteristic of high lignin biomass (Pongamia shells). Renewable Energy 2015;80:415-23. https://doi.org/10.1016/j.renene.2015.02.024.

[46] Parascanu MM, Puig-Gamero M, Soreanu G, Valverde JL, Sanchez-Silva L. Comparison of three Mexican biomasses valorization through combustion and gasification: Environmental and economic analysis. Energy 2019;189:116095. https://doi.org/10.1016/j.energy.2019.116095.

[47] Pattanayak S, Hauchhum L, Loha C, Sailo L. Feasibility study of biomass gasification for power generation in Northeast India. Biomass Conversion and Biorefinery 2021. https://doi.org/10.1007/s13399-021-01419-8.

[48] Samson R, Mani S, Boddey R, Sokhansanj S, Quesada D, Urquiaga S, et al. The Potential of C 4 Perennial Grasses for Developing a Global BIOHEAT Industry. CRC Crit Rev Plant Sci 2005;24:461-95. https://doi.org/10.1080/07352680500316508.

[49] Moutsoglou A. A comparison of prairie cordgrass and switchgrass as a biomass for syngas production. Fuel 2012;95:573-7. https://doi.org/10.1016/j.fuel.2011.12.016.

[50] Emery I, Mbonimpa E, Kumar S, Muthukumarappan K, Wei L, Jahndideh A, et al. Life cycle assessment of drop-in biofuels from prairie cordgrass. 2017 ASABE Annual International Meeting, 2017. https://doi.org/10.13031/aim.201701357.

[51] Jozami E, Sosa LL, Feldman SR. *Spartina argentinensis* as feedstock for bioethanol. Applied Technologies & Innovations 2013;9:37-44.

[52] Kunst C, Bravo S, Moscovich F, Herrera J, Godoy J, Vélez S. Fecha de aplicación de fuego y diversidad de herbáceas en una sabana de *Elionorus muticus* (Spreng) O. Kuntze. Revista chilena de historia natural 2003;76:105-15. https://doi.org/10.4067/S0716-078X2003000100010.

[53] Massa ES, Oakley LJ, Prado DE, Feldman SR. Resiliencia de un pajonal de *Panicum prionitis* Nees bajo distintas alternativas de manejo. Ecologia Austral 2016;26:236-45.

[54] Dong Y, Dong L, Jing Y, Qiang N. Gas-heat-electricity triple cogeneration technology for gasification of *Spartina*. Transactions of the Chinese Society of Agricultural Engineering 2007;8.

[55] Jungers JM, Sheaffer CC, Fargione J, Lehman C. Short-term harvesting of biomass from conservation grasslands maintains plant diversity. GCB Bioenergy 2014;7:1050-61. https://doi.org/10.1111/gcbb.12195.

[56] Sosa LL, Jozami E, Oakley LJ, Montero GA, Ferreras LA, Venturi G, et al. Using C4 perennial rangeland grasses for bioenergy. Biomass and Bioenergy 2019;128:105299. https://doi.org/10.1016/j.biombioe.2019.105299.

[57] Lal R. Soil carbon sequestration to mitigate climate change. Geoderma 2004;123:1-22. https://doi.org/10.1016/j.geoderma.2004.01.032.

[58] Chang J, Ciais P, Viovy N, Vuichard N, Herrero M, Havlík P, et al. Effect of climate change, CO_2

trends, nitrogen addition, and land-cover and management intensity changes on the carbon balance of European grasslands. Global Change Biology 2016;22:338-50. https://doi.org/10.1111/gcb.13050.

[59] Lorenz K, Lal R. Carbon Sequestration in Agricultural Ecosystems. Cham: Springer International Publishing; 2018. https://doi.org/10.1007/978-3-319-92318-5.

[60] Conant RT, Cerri CEP, Osborne BB, Paustian K. Grassland management impacts on soil carbon stocks: a new synthesis. Ecological Applications 2017;27:662-8. https://doi.org/10.1002/EAP.1473.

[61] Maillard É, Angers DA. Animal manure application and soil organic carbon stocks: a meta-analysis. Global Change Biology 2014;20:666-79. https://doi.org/10.1111/GCB.12438.

[62] Knicker H. How does fire affect the nature and stability of soil organic nitrogen and carbon? A review. Biogeochemistry 2007 851 2007;85:91-118. https://doi.org/10.1007/S10533-007-9104-4.

[63] Johansen MP, Hakonson TE, Breshears DD. Post-fire runoff and erosion from rainfall simulation: Contrasting forests with shrublands and grasslands. Hydrological Processes 2001;15:2953-65. https://doi.org/10.1002/hyp.384.

[64] Zhao H, Tong DQ, Lin Q, Lu X, Wang G. Effect of fires on soil organic carbon pool and mineralization in a Northeastern China wetland. Geoderma 2012;189-190:532-9. https://doi.org/10.1016/j.geoderma.2012.05.013.

[65] Bikila NG, Tessema ZK, Abule EG. Carbon sequestration potentials of semi-arid rangelands under traditional management practices in Borana, Southern Ethiopia. Agriculture, Ecosystems and Environment 2016;223:108-14. https://doi.org/10.1016/j.agee.2016.02.028.

[66] Jens F, Peters JF, Iribarren D, Dufour J. Life cycle assessment of pyrolysis oil applications. Biomass Conversion and Biorefinery 2014;5:1-19. https://doi.org/10.1007/s13399-014-0120-z.

[67] Brewer CE, Schmidt-Rohr K, Satrio JA, Brown RC. Characterization of biochar from fast pyrolysis and gasification systems. Environ Prog Sustain Energy 2009;28:386-96. https://doi.org/10.1002/ep.10378.

[68] Muench S, Guenther E. A systematic review of bioenergy life cycle assessments. Appl Energy 2013;112:257-73. https://doi.org/10.1016/j.apenergy.2013.06.001.

[69] Pinilla Vargas, Diana K. Influencia del clima, la vegetación y el hombre sobre la frecuencia, intensidad y distribución de los incendios en Argentina. Universidad de Buenos Aires, 2012.

[70] Verón SR, Jobbágy EG, Di Bella CM, Paruelo JM, Jackson RB. Assessing the potential of wildfires as a sustainable bioenergy opportunity. GCB Bioenergy 2012;4:634-41. https://doi.org/10.1111/j.1757-1707.2012.01181.x.

Stage	Reference flow	Process	Value	Unit	Reference/emission factor
Field stage	1.16 Mg of bales	Bales load	1.4	Bale	(Wernet et al., 2016) [35]
		Anthill knocking down; Mower; Hay Rake; Baler	0.4	Hours	(Wernet et al., 2016)*
		Land Occupation	2669.5	m^2	
		Shipping 30 km	33.3	tkm	(Blonk Agri Footprint BV, 2015a, 2015b) [36, 37]
Industrial stage	1.22 MWh of power (1 MW injected to the grid + 0.22 MWh for the industrial stage)	Biochar Combustion	49.6	kg	Emission factor of 3.2 grams of non biogenic CO_{2eq} per MJ obtained form Huang et al (2013) [38]; higher heating value of biohar was obtained from Brewer (2012) [39]
		Syngas Combustion	2303.8	m^3	NOx and N_2O emissions adapted from IPCC (2013) [40]

*adapted with Primary data of diesel consumption

Table 1: Processes considered ASp to accomplish with the functional unit (to deliver 1.0 MWh of electricity to the power grid)

Stage	Reference flow	Process	Value	Unit	Reference/emission factor
Field stage	8.87E-5 Mg of bales	Bales load	1.4	Unit	(Wernet et al., 2016) [35]
		Anthill knocking down; Mower; Hay Rake; Baler	0.4	Hours	(Wernet et al., 2016)* [35]
		Land Occupation	2669.5	m^2	Personal data
		Shipping 30 km	33.3	tkm	(Blonk Agri Footprint BV, 2015a, 2015b) [36,37]
Industrial stage		Auxiliary equipment	7.15E-03	MJ	Personal data
		Pelletizing	1.95E-02	MJ	Personal data
		Grinding	6.22E-03	MJ	Personal data
		Chopping	9.15E-03	MJ	Personal data
		Bagging	4.75E-04	MJ	Personal data
		Packaging film, low density polyethylene {GLO}| market for | APOS, U	4.75E-04	Kg	(Wernet et al., 2016) [35]
		Wood pellet factory {GLO}| market for | APOS, U	1.43E-09	Unit	(Wernet et al., 2016) [35]
		Furnace, pellets, 9kW {CH}| production | APOS, U	2.78E-06	Unit	(Wernet et al., 2016) [35]
Distribution to Market		Transport, truck >20t, EURO1, 100%LF, default/GLO Mass	2.38E-03	tkm	(Blonk Agri Footprint BV, 2015a, 2015b) [36,37]
Use Stage		Pellet combustion	1.00	MJ	
		Furnace, pellets, 9kW {CH}| production | APOS, U	2.78E-06	Unit	(Wernet et al., 2016) [35]
Ash disposal		Wood waste, unspecified, combusted in industrial boiler/US	7.54E-06	Mg	(USLCI, 2012) [41]

Table 2: Processes considered for ASh to accomplish with the functional unit (to deliver 1.0 MJ of useful thermal energy for residential heating.)

Process to be replaced	**values per functional unit for each Alternative scenarios**				**Unit**	**Reference**	**External process selected for replacement**	**Value**	**Unit**
	ASp$_{o}$	ASp$_{50}$	ASp$_{90}$	ASh					
Grassland Burning	2923	2923	2923	0.2	m^{2}	IPCC	biomass dr matter harvest	337.1	g*m^{-2}
Heat, central or small-scale, natural gas {RoW}*	742.3	742.3	742.3		MJ	Ecoinvent 3.5	Biochar combustion for heat	46.8	kg
		4090			MJ	Ecoinvent 3.5	Syngas heat obtention from cogeneration	2303.8	m^{3}
			7360		MJ	Ecoinvent 3.5	Syngas heat obtention from cogeneration	2303.8	m^{3}

* *Heat, central or small-scale, natural gas {RoW}| market for heat, central or small-scale, natural gas | APOS, U

Table 3: Avoided processes in each alternative scenario.

Figures 1 and 2 were realized in the following website
http://sankey-diagram-generator.acquireprocure.com/

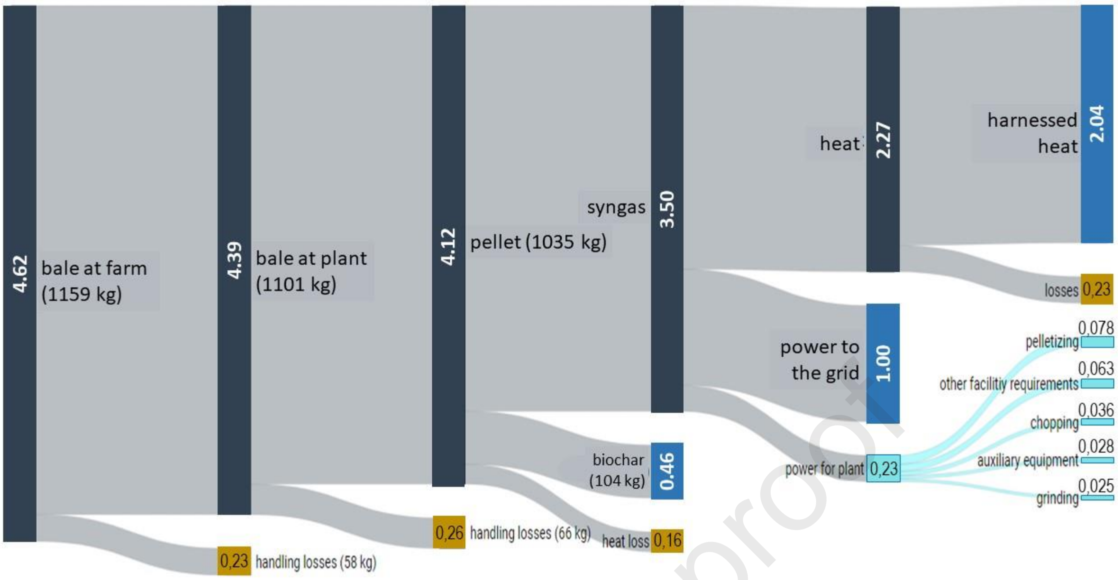


Fig. 1 Energy flow for ASp$_{90}$ (numbers expressed in MWh). Blue color bars represent the products obtained from each system.

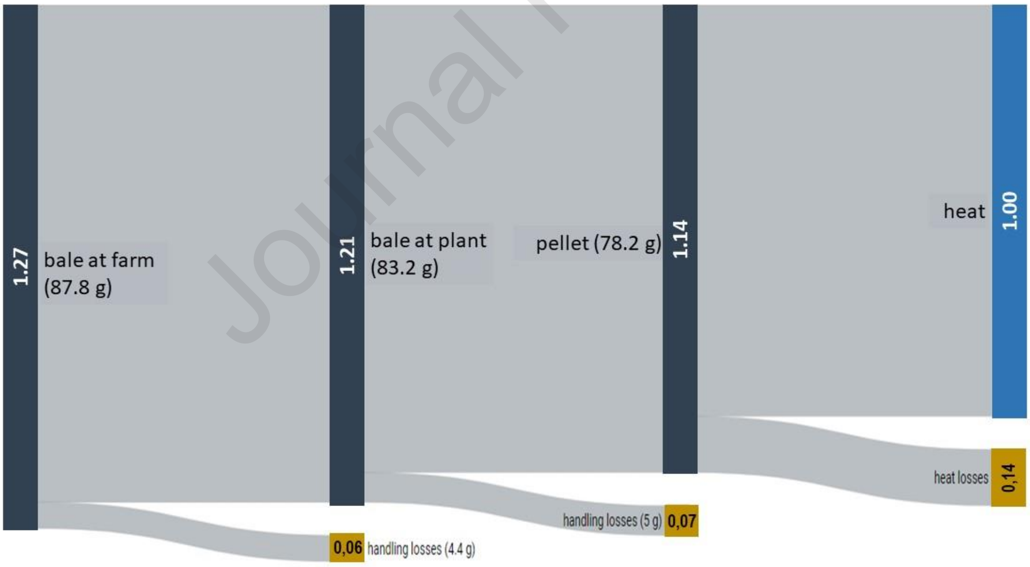


Fig. 2 Energy flow for Ash (numbers expressed in MJ). Blue color bars represent the products obtained from each system.

Figures 3 and 4 were realized in the following website:

https://lucid.app/users/login#/login?referredProduct=lucidchart

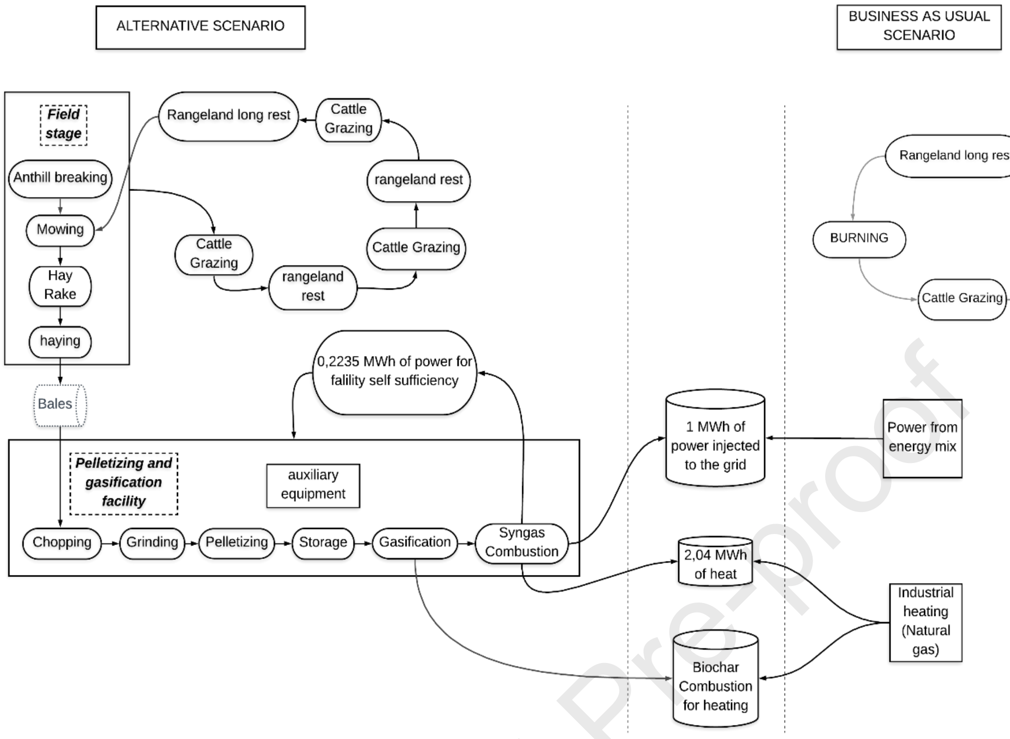


Fig. 3 System product of ASp_{90} and BAUp scenarios for electricity production

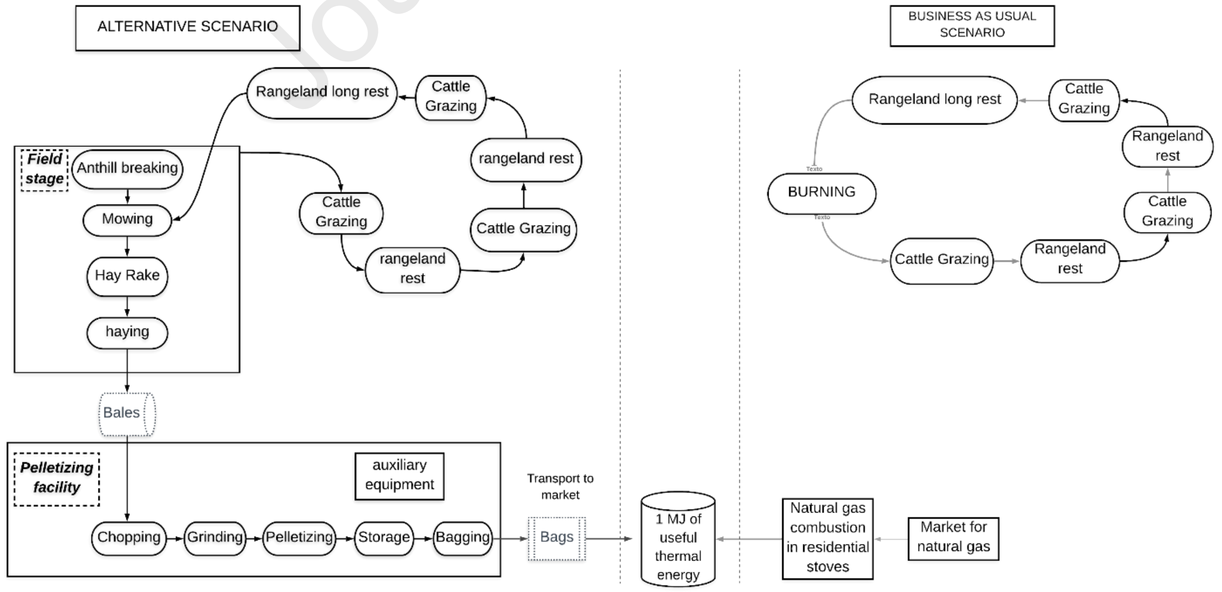


Fig. 4 System product of ASh and BAUh scenarios for residential heating

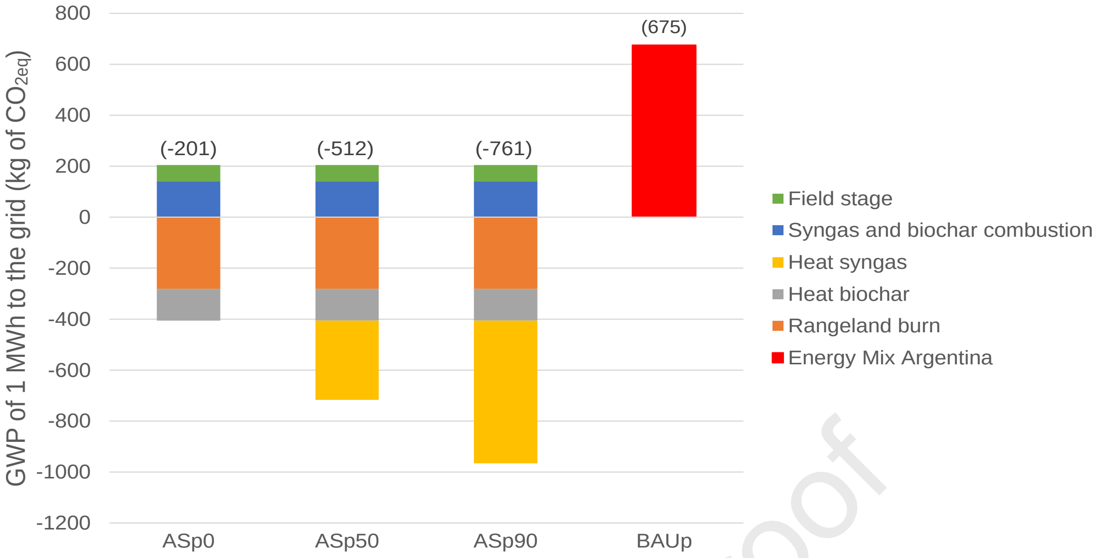


Fig. 5 GWP results from ASp and BAUp scenarios. Values between parentheses indicate the net result.

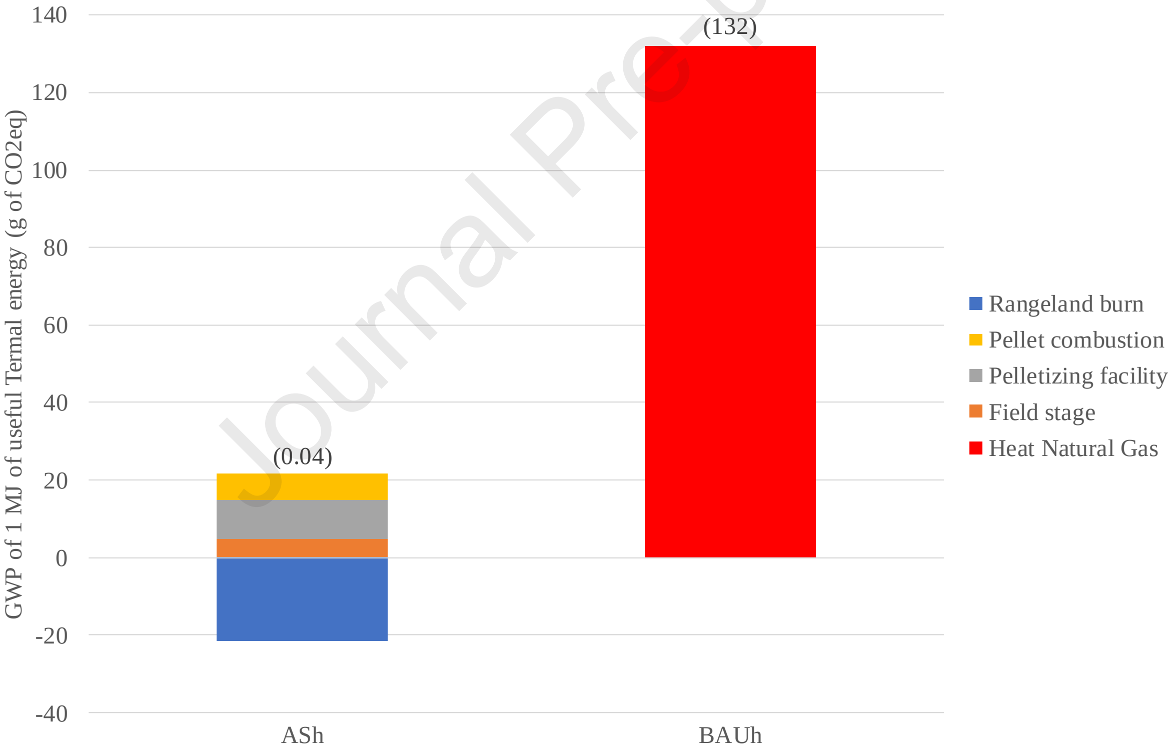


Fig. 6 GWP results from ASh and BAUh scenarios. Values between parentheses indicate the net CO_2eq result.

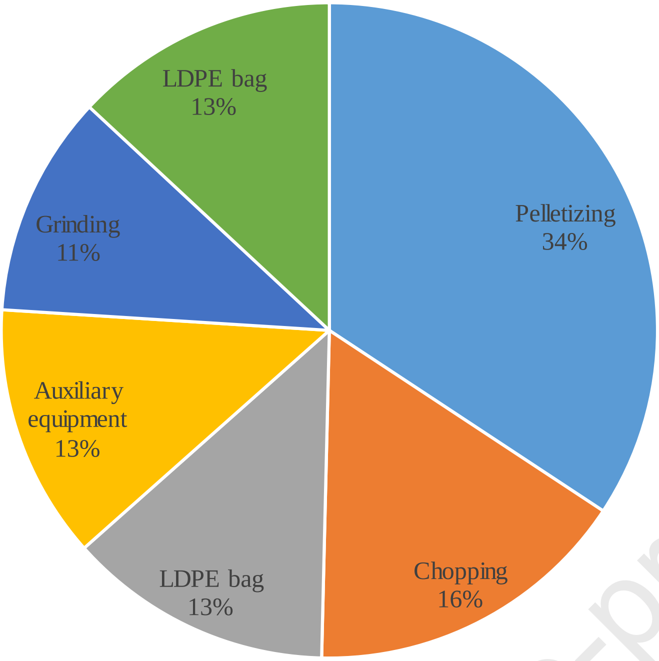


Fig. 7 GWP breakdown from ASh and BAUh scenarios. Values between parentheses indicate the net CO_2eq result.

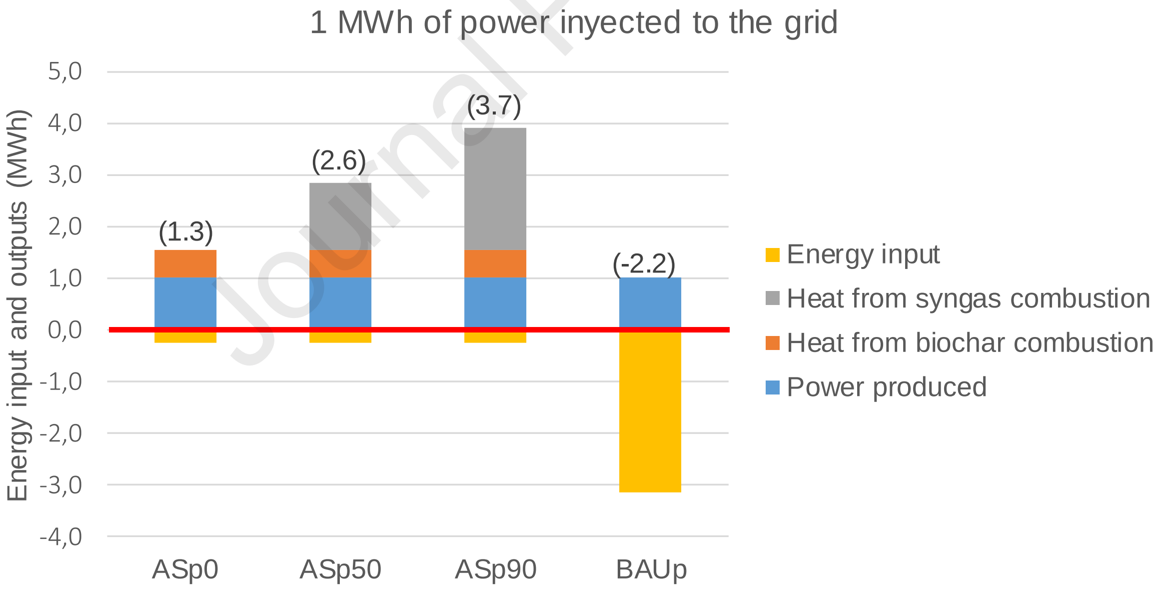


Fig. 8 Energy balance according to CED LHV method for the power assessed systems. Values between parentheses indicate the net energy balance per MWh of energy delivered to the grid.

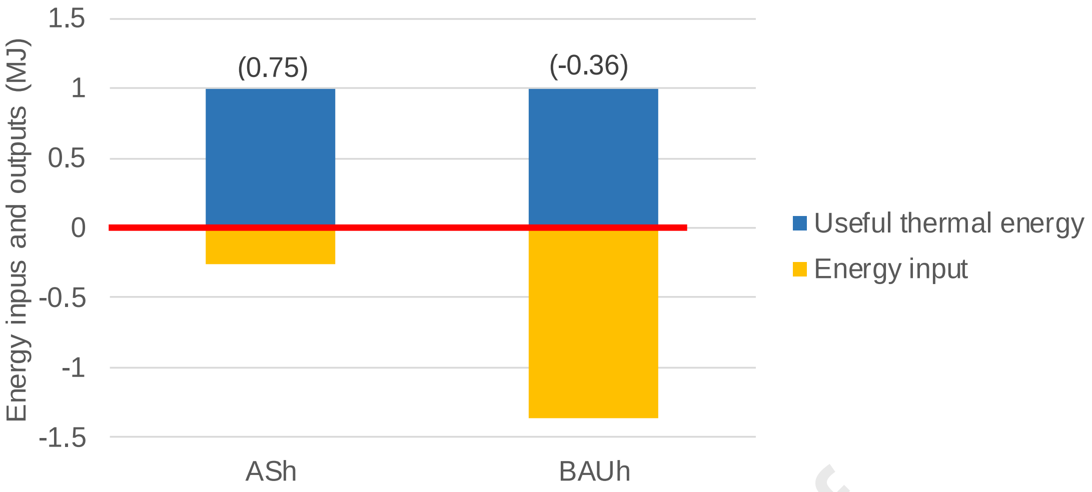


Fig. 9 Energy balance according to CED LHV method for the residential heat assessed systems Values between parentheses indicate the net energy balance per MJ of useful thermal energy

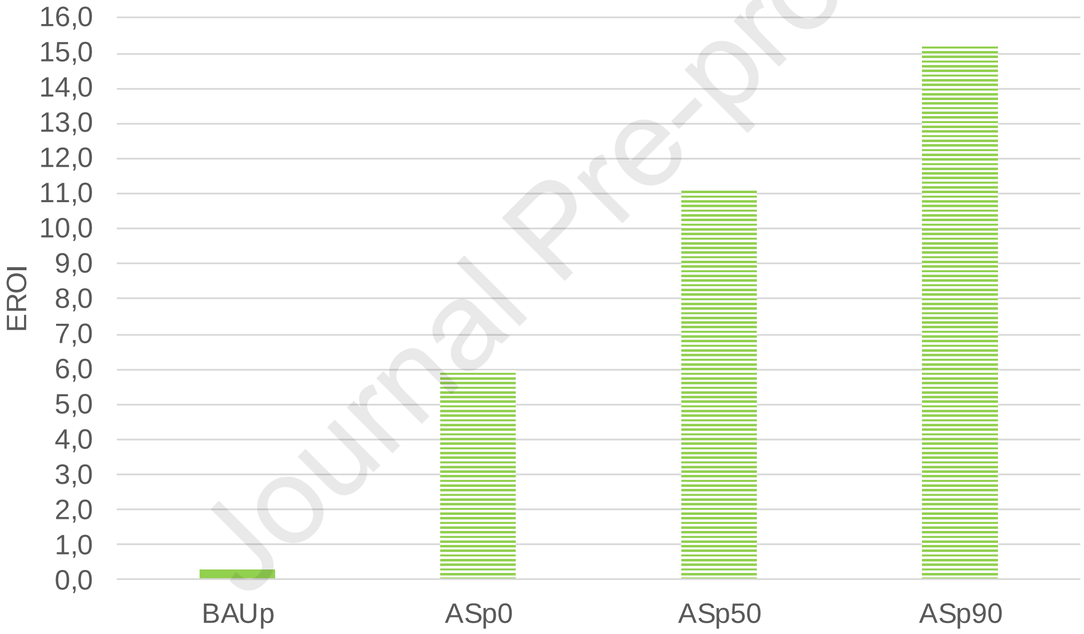


Fig. 10 Energy Return on Investment of ASp vs BAUp

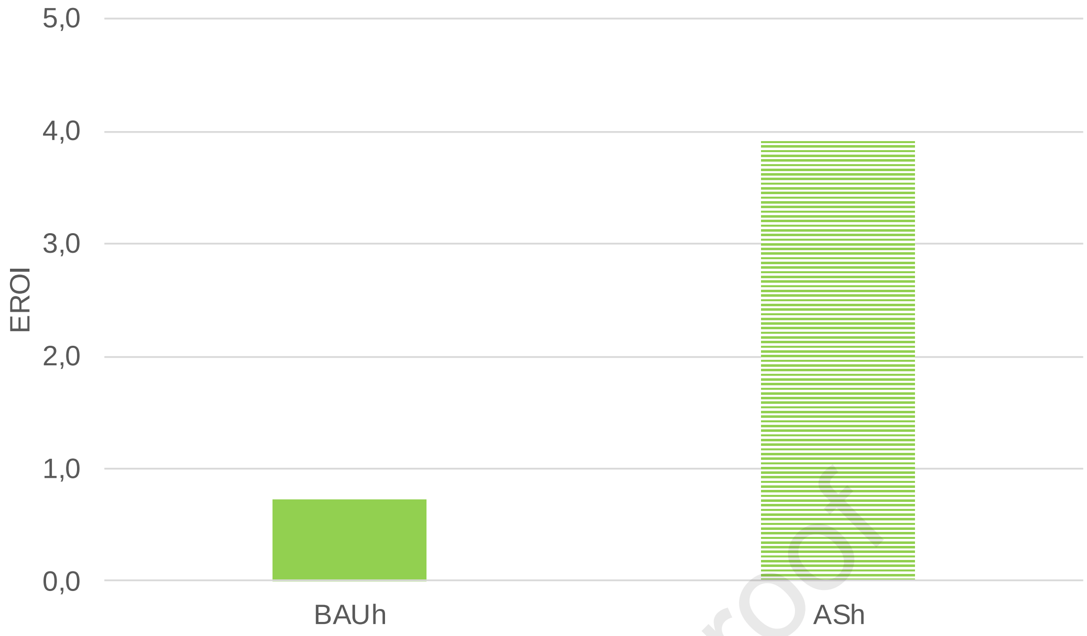


Fig. 11 Energy Return on Investment of ASh vs BAUh

Statements and declarations

Funding

Field work was accomplished thanks to financial support derived from Universidad Nacional de Rosario and the Agencia Santafesina de Ciencia, Tecnología e Innovación.

Data Availability

The datasets generated and analyzed during the current study are not publicly available as part of the data will be published in the main author thesis, but are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare no competing interests.

Author Contributions

The present research was accomplished in the context of the first author (Emiliano Jozami) doctoral thesis. Dr. Susana Feldman is the director and Dr. Bárbara Civit is the co-director and both collaborated with the writing of the paper as well as guiding Emiliano along the process of the LCA. Dr. Fernando Mele collaborated in grammar of the paper and with figures and tables. Roxana Piastrellini helped with the writing of the paper and collaborated with the data needed for the software Simapro.