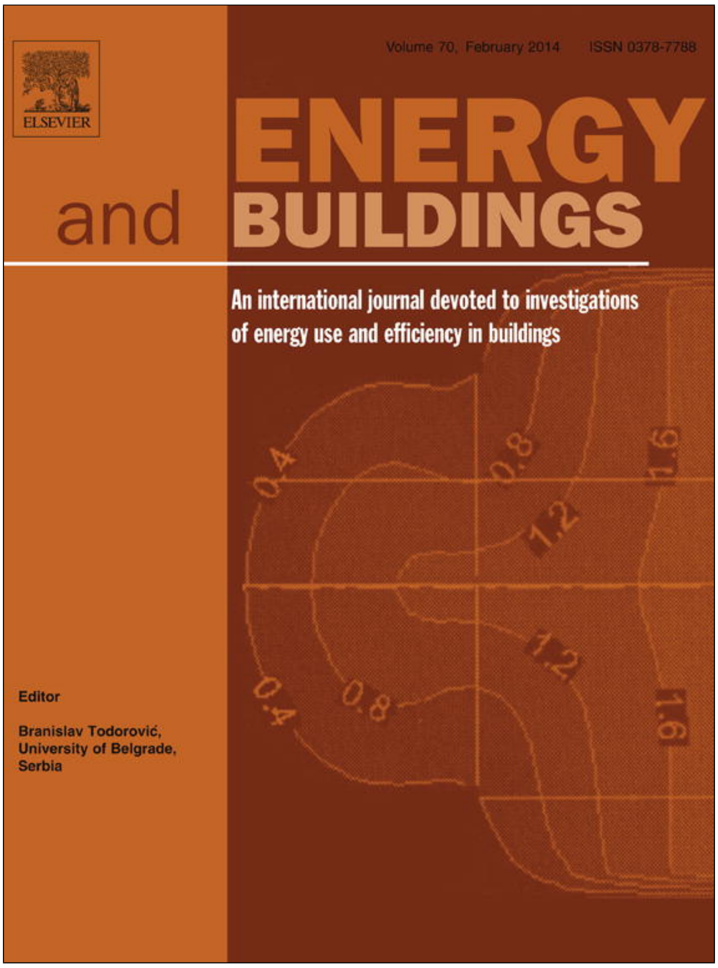
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Energy and carbon embodied in straw and clay wall blocks produced locally in the Andean Patagonia

Alejandro D. González [a,b,*]

[a] Centro Transdisciplinario de Estudios Ambientales y Desarrollo Humano Sostenible, Universidad Austral de Chile, Valdivia, Chile
[b] INIBIOMA, CCT-Comahue, Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Bariloche, Argentina

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ABSTRACT

The production and use of cereal straw as a base material to make building envelopes in the Andean Patagonian region have been investigated. Energy used and greenhouse gases (GHGs) emitted in local manufacturing of construction materials for walls based on wheat straw were obtained, as well as cropland required for different construction techniques. Two options for the use of straw to fill envelop walls were investigated: the direct use of straw bales, whether in whole or in halves, and the manufacturing of straw-clay blocks. The former has the best thermal conductivity but requires larger cultivation areas to satisfy wall demands, whilst the latter could be an option including moderate thermal efficiency and better cropland performance. Per wall surface unit, energy use and GHG emissions of all straw options were significantly lower compared to fired bricks or to concrete blocks. Furthermore, all straw options analysed result in significantly better thermal performance than current choices of fired bricks or concrete blocks, which are commonly used in the region. The present results show a relevant role of renewable agricultural products in lowering impacts of building materials, as well as options for sustainable production.

1. Introduction

Building with low-input materials from local sources is a challenge with multiple benefits; more so if building materials are made from renewable resources. In a recent work, Seyfang [1] discussed the need for energy policies that consider construction with renewable and local resources. The benefits include: social empowering labour and businesses; low-impact recycling at construction and demolition; autonomy that increases resilience to future fossil fuel scarcity; easier adaptation of materials and techniques to local requirements; mitigation of environmental impacts, in particular lower energy and carbon footprints. Even though techniques and characteristics of materials and skills in this area would not apply in a standard way in the majority of cases, the niche experience and lessons can bring up good practices in mainstream constructions [1].

Straw is a renewable resource that has been extensively used in traditional and modern building practices. It has the great advantage to be a residue from harvesting cereal grains, presently the largest food group for human consumption [2]. Straw from all major cereals is suitable and convenient as construction material in a range from small scale businesses to large industries. For instance, the property allowing the use of temperature and pressure to bind straw without the use of added resins makes the material suitable for a diversity of industrial applications; in particular green-labelled products for acoustic insulation and low density boards (c.200 kg/m^3) [3]. Other fibres from agriculture, like flax, hemp, and jute [4], and corn's cob [5] are also suitable as building materials with outstanding properties; although the present work will concentrate on cereal straw.

Ashour et al. [6] have recently investigated the performance of straw bales in a house built in the south of Germany. They have found very good thermal response of straw bale walls to cold conditions, and promising results on low moisture content, kept under 15%, which is the safe level for straw durability. There has also been research on reinforcing earth plasters with straw and wood shavings. Advantages for both thermal and hygroscopic performances were found, giving the use of straw better results than wood shavings, and barley straw lower thermal conductivity than wheat straw [7]. Due to both, straw thermal properties and thickness, straw bale walls have a thermal resistance even higher than industrially made insulations. However, the use of whole straw bales involves large wall thicknesses that are not always possible or desired in

* Correspondence address: Centro Transdisciplinario de Estudios Ambientales y Desarrollo Humano Sostenible, Universidad Austral de Chile, Valdivia, Chile. Tel.: +56 63 2221915.
E-mail addresses: adgonzalez@uach.cl, gonzalezad@comahue-conicet.gob.ar, ale.agonzalez@gmail.com

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the design. Experimental constructions with half straw bales, cut on site with chainsaw were also found to be convenient [8], and will be discussed later. On the other hand, the use of whole straw bales requires large amounts of the resource, and if not available locally it can imply costly transportation. Therefore, the manufacturing of blocks with cereal straw and earth bindings were proposed as low impact alternative [9]. In the Andean Patagonia, several techniques including cereal straw are currently use in buildings: (1) direct use of straw bales for walls, whether in whole or in halves; (2) a mix of straw, clay and soil to fill quincha-type walls; (3) walls shaped by on-site framing straw and clay; and (4) manufacturing of straw-clay blocks. The present work deals with techniques (1) and (4). In recent decades, the use of straw bales has increased in the US and Europe, as well as in the Andean region of Patagonia. For the scope of the present work, this area comprises the Andean region of Argentina extending between latitudes 39° S and 44° S.

A note on heating efficiency and current energy situation in Argentina is firstly in order. At present, fired bricks and concrete blocks are the most common materials for building envelopes, which mostly have reinforced concrete framing. Wood is preferred for frames and indoor applications, but not as wall envelopes. The current construction lack thermal insulation in walls and floors, while cavity roofs are, in the best cases, filled with 2–5 cm of glass wool. Even though the Andean region of Patagonia has a very cold climate, no mandatory thermal requirements are included in building codes. The region is included in the coldest bioclimatic zoning of Argentina [10]; however, heating efficiency of dwellings in this cold region and in the temperate-warm city of La Plata was found to be similar [11]. The cities of Bariloche, El Bolsón and Esquel have average annual temperatures ranging from 7 °C to 9 °C, and heating degree-days between 3000 and 4500. Near these cities, the largest ski resorts in South-America are located and over a million tourists visit yearly. Climate conditions and human activities would require buildings designed accordingly; nevertheless, only around 5% of constructions have some thermal insulation. The consequence is very high energy consumption in heating, reaching between 3 and 5 times more heating energy per m^2 as used in regions with similar climate in Sweden or Germany [12]. Households and businesses afford this level of energy consumption due to very large subsidies. The high energy consumption also contributes large amount of CO_2 and other contaminant gases. For instance, in the city of Bariloche, the average one-family household with natural gas provision uses 550 kWh/m^2 year, which leads to emissions of 3.9 tonne CO_2/person year [11].

Low efficiency in Argentinean buildings is not only found in envelopes but also in furnaces. The most used gas furnace in households is a metal device with direct entrance and outlet chimneys, and has been shown to have very low thermal efficiency [13]. Moreover, this heater's design could be greatly improved with simple modifications and low cost additions, increasing thermal efficiency in as much as 50% with an added cost not larger than 10% of sale value [14]. In spite of the feasibility and low cost, the improvements that have been suggested to manufacturers and to authorities were not done, possibly because no real economic benefit could be identified alongside with the availability of cheap subsidised natural gas. We should however bear in mind that the sustainability of the gas provision in Argentina is at risk, with reserves decreasing rapidly. In the last decade, the country, a gas exporter in 2003, became net importer. Large demands and poor investments due to low regulated prices contributed to the need of natural gas imports, which have increased drastically since 2008 with the setting of two new Liquefied Natural Gas (LNG) gasification ports, located near the cities of Bahía Blanca and Zárate. Natural gas provision for 2011 and 2012 was so critical that around 65 shipments of LNG by tankers arrived at the two ports in 2012. In addition, imports by pipelines from Bolivia increased to c.10% of the gas used in 2012, while another 10% was delivered as LNG. The cost of both options at port of entry are between 10 and 18 times higher than what is paid by households in the region covered by the present research [15].

On the other hand, common construction materials like bricks and cement are manufactured in Argentina but far away from the region of Andean Patagonia considered here. The main energy resources for manufacturing these materials are natural gas and electricity. In 2009, electricity was generated with 51% natural gas, 28% hydro, 10% fuel and diesel oil, 7% nuclear, and 4% coal and biomass. Natural gas contributed with 52% and oil 41% to the primary energy supply in 2009 in Argentina [16]. Therefore, fossil fuels and particularly natural gas are key factors in energy supply in Argentina. The total energy production in the country reached a maximum in 1999, and had levelled off since. Therefore, energy supply should be carefully considered on sustainability analysis for the building sector, both in the construction stage and the building operation phase.

The making of cement, bricks, and metals relies heavily on the use of natural gas, and production is made only where large pipelines are available. Thus, transport between 700 km and 2000 km are required to deliver actual construction materials to the Andean Patagonia. Transportation takes place by truck mainly from Mendoza, Neuquén, Comodoro Rivadavia, and Buenos Aires, through narrow highways comprising nearly 400 km across mountain roads. No railways are used for this transport in Patagonia. Cement is transported between 700 and 1000 km, steel between 1500 and 1800 km, and bricks between 700 and 1000 km, depending on the city considered. Wood is mostly local and the availability regular, whether from plantations or native varieties. Therefore, a risk is identified for future sustainability when building with materials transported long distances into areas of difficult access. This is also a motivation for the present investigation on a local possible way to build more efficient dwellings.

The straw is from local cereal producers, and frames are built mostly with wood from local sources. The traditional use of straw-bale was compared with the manufacturing of building blocks made with straw and clay, and both compared to fired bricks and concrete blocks. Detailed account of manufacturing of straw-clay blocks will be discussed, along with energy use and GHGs emitted in the process. Since the technique involves intensive human labour, an assessment on energy and carbon footprint of labour will be considered. The land area required per square metre of envelope when using straw bale or clay-straw blocks is relevant as local production is limited to the suitable agricultural valleys of the region. The sustainability of agricultural soils will also be discussed, to assess the maximum straw production without affecting soil organic matter and fertility.

2. Materials and methods

2.1. Description of the straw-clay construction system studied

The house building techniques described here have been extensively used, and detailed data on practical construction matters and inputs have been obtained from a local enterprise specialised in straw-clay building. As for 2013, the enterprise has built 10 one-family houses with living areas ranging from 65 m^2 to 170 m^2 in suburban and rural areas, and a large public building of 600 m^2 where functions a private alternative medicine clinic, located in downtown El Bolsón. This city is located 20 km away from the farm and the construction site chosen for this study. Straw bale constructions are also common; however, this technique is very similar to other locations worldwide and has been well described elsewhere [6]. Due to seismic requirements in the region,

Fig. 1. Straw-clay blocks set to dry.

Fig. 2. 80 m² one-family house with exterior walls of straw-clay blocks.

Fig. 3. 120 m² one-family house with exterior walls of straw-clay blocks.

independent structures made either in wood or metal are set, while the straw options are used as envelope fillings. It is to note that so far, neither the houses nor the large business building mentioned have been systematically studied to assess durability and water proofing properties, which also depends on regional climatic conditions.

Straw-clay blocks were manufactured manually by mixing straw with a solution of clay in water. Although straw is required loose at the beginning of the process, bales were transported to the construction site to minimise work and volume in transport. The straw and clay were mixed in a gasoline-powered mixer, and then set on a large 300 μm-thick plastic for further hand mixing and distribution. In this stage the appropriate level of humidity is checked. A wooden cast is used to shape blocks into 0.25 m × 0.21 m × 0.50 m, and then they are air dried outdoors. Fig. 1 depicts the spreading of the blocks for ambient air drying by the construction site.

The weight of dry straw-clay blocks varies between 5.5 kg and 7 kg, and so the density ranges between 210 kg/m^3 and 270 kg/m^3. Large variations are expected in the mostly handmade manufacturing process and the manufacturer estimate an average density of 250 kg/m^3. When made into a wall with sand and clay mortar the resulting density is estimated at 400 kg/m^3. The manufacturer informed that making 1000 blocks takes 240 h of labour, and groups of 3–4 people are usually involved. At an average rate of 7 blocks per m^2 of wall, 1000 blocks are enough to fill the envelope of a 120 m^2 one-family house and some interior walls too. Clay was mined nearby, and 20 km transportation by a 10-tonne truck was considered. In average, the professional group is able to produce 35–40 straw-clay blocks per person per day. These data will be relevant to obtain energy and carbon footprints including human labour, which must be considered as it is a large part of the manufacturing process here.

Note that several steps can be done by personnel with no expertise. Even for setting up walls, once the framing structure is done by professionals, the method to perform the envelope wall is suitable for self building with volunteer work, which is in fact common in the region of study. However, the quantities reported herein were obtained from a professional building group specialised in this construction typology, so the results are representative of footprints that can be expected from small and medium size businesses.

Figs. 2 and 3 show examples of one-family houses of 80 m^2 and 120 m^2 living area build with the technique described here. In both cases the frames were timber, and the walls were filled with straw-clay blocks set with clay-sand mortar. Finishing plaster was done with sand and clay in Fig. 2 and with sand and calk in Fig. 3. In one case a green roof was chosen and in the other the roof is covered by conventional metal sheet.

In addition to the new constructions shown above, the technique is very convenient for thermal retrofitting of social housing. An example of the retrofitting of a wooden cabin, which had wooden envelope with no insulation, is shown in Fig. 4. To set up walls, straw-clay blocks were joined by sand-clay mortar. The holes observed in the blocks (Fig. 4) are filled with loose straw as the wall is set up, improving thermal insulation and levelling the surface to apply mortar. The labour for this retrofit was done in cooperation of one professional with volunteers learning the technique as working.

Fig. 4. Straw-clay blocks used to improve thermal insulation in a wooden 30 m² house.

The thermal conductivity for the present straw-blocks was not measured; however, based on similar materials reported by other authors the thermal conductivity can be estimated under 0.18 W/m K. This upper-level value corresponds to straw and clay blocks with a density of 440 kg/m^3 investigated by Goodhew and Griffiths [9]. Baled wheat straw has thermal conductivity between 0.07 and 0.09 W/m K, and a density between 60 kg/m^3 and 90 kg/m^3. In the present work, the wheat baled density provided by the local farmer was 70 kg/m^3. Not having a better estimate for the straw-clay blocks introduced here, the upper value of 0.18 W/m K will be assumed as the probable conductivity for the comparisons below.

2.2. Straw and grain production in the Golondrinas Andean Valley

We have obtained data from the major producer of cereal grain and straw in the Golondrinas valley (42°04 S, 71°30 W latitude), located in the northern part of the Chubut Province, in Argentina. Cereal production in the Andean Patagonia has been a major activity until the 1950s. At the time, wheat from the region has gained international fame for its high quality, then production rose and local value-added industries started making flour and pasta. For reasons beyond the scope of this article, in 1949 the central government favoured producers of The Pampas with subsidies, forcing Patagonian cereal producers out of large scale operations. At present, cereal farmers focused on quality, and in general they cultivate with minimum use of pesticides or synthetic fertilisers. Average annual temperatures between 8 °C and 10 °C are found in the region, favouring wheat, rye, barley, and oat cultivation. All these cereals provide straw with high carbon and low nitrogen content, suitable for construction. The builder's enterprise surveyed during the present work used wheat straw, so the energy and GHG footprints were calculated here for this cereal.

The wheat farm surveyed sow with the method of no tillage. This is so to reduce soil degradation and energy use in machinery. Weed control is done with herbicide previous to the cultivation cycle. Seed is self provided, saved from previous harvests. Once mature, the grain is harvest with a combine, which also cuts the straw to a chosen height. Afterwards, another machine is used to bale. Only half the straw available is harvested and baled, leaving the other half on the ground for decomposing. According to the farmer, this procedure has guaranteed a constant level of organic matter in the soil, and will be discussed in Section 3.4. Under these conditions, 150 straw bales of 10 kg each were obtained per ha. No irrigation is applied to the fields surveyed.

2.3. Energy and GHG emissions of human labour

As shown, the production of straw-clay blocks is very intensive in human labour; therefore an account of its energy and GHGs is needed for a realistic approach. Due to large differences in country activities, technology availability, foods, lifestyles, and regional differences within a country, footprints for human labour are difficult to assess accurately. Several authors have attempted approaches to give the best possible estimates. Pimentel [17] has used a criteria based on per capita country's consumption of energy, assuming all primary energy used in a country is invested in maintaining its working capacity. This approach gives an estimate of what recently Jiao et al. [18] defined as the energy expenditure needed to support the workers lifestyle. However, Jiao et al. [18] include a second energy contribution from food that a worker needs to consume to maintain a physical activity ratio, which is, in constructions, usually much larger than the basal metabolic rate [19]. This approach is interesting because it captures not only the food required to be able to perform the physical activity, but also the whole household energy expenditure which makes labour impacts among countries distinct. For instance, energy expenditure per hour of human labour in the US results much larger than in Kenya, India and Indonesia, in spite that food calories required to achieve the work might be similar [17].

In Argentina, in 2010, total Primary Energy Supply was 77.5 GJ/capita (1.85 toe/capita), and CO_2 emissions 4.21 tCO_2e/capita [20]. Considering 8760 h per year it yields energy use of 8.8 MJ/h, and GHG emissions 0.48 kg CO_2e/h. In addition, assuming a very high caloric diet for straw-clay blocks manufacturing, the additional energy for labour is 0.61 MJ/h, and the additional GHG emissions 0.26 kg CO_2e/h. GHG emissions for a given caloric content of the diet was obtained from Pradhan et al. [21], who assessed food consumption impacts for a large variety of diets and countries worldwide. Therefore, the average energy and GHG emissions for an hour of human labour in Argentina are estimated at 9.5 MJ/h and 0.74 kg CO_2e/h, being the largest contribution not from the food required, but from the country's energy expenditure to maintain lifestyles.

When local conditions are known, another way of estimating the impact is accounting for a typical household consumption. This can reflect the regional variability, which in Argentina is relevant due to diversity of climates and access to energy [11]. As mentioned, in the region of study average energy use in a one-family dwelling of 3 persons is 67 GJ/cap.year, while transportation based on 15,000 km/year by car for the household adds 15 GJ/cap.year of transport energy consumed. Assuming a very high caloric diet as explained above, around 5 GJ/cap.year from food consumption should be added. This estimation for a household with regional characteristics found in Andean Patagonia leads to 10.6 MJ/h and 0.88 kg CO_2e/h for human labour.

Both criteria, country-based and regional-based, give similar results, and hereinafter the values of 10.6 MJ/h for energy footprint and 0.88 kg CO_2/h for carbon footprint will be considered, respectively, for an hour of human labour in the Andean Patagonia.

2.4. Energy and GHG inventories

Energy and GHG emissions inventories were performed using standard procedures described in the IPCC's Guidance for Greenhouse Gas Inventories [22], combining Tier 1 and Tier 2 methodologies when information is available, i.e. when local estimates (Tier 2) are not known default values were used instead (Tier 1) [23]. Agricultural inputs and labour for straw were obtained from the local wheat producer, while inputs and hand labour for manufacturing straw-clay blocks were obtained from the construction enterprise, both mentioned above. These data were combined with specific energy and GHG impacts per unit of each material and fuel considering local specifications as far as possible. Local energy and GHG footprints could not be established for certain materials, and thus global data were obtained from previous works. For instance, EU and US data on energy and GHG emissions from fertiliser and herbicide manufacturing were used. This approximation represents quite well the reality of local conditions, as Argentinean agriculture is mostly for export and products in the local market are international brands, with some agrochemicals even made in Argentina and exported, like herbicides.

Data on long distance transport from EU sources was compared by consultation with a local transportation company. Local 40-tonne long distance trucks are from international brands (Scania, Volvo, Mercedes Benz, etc.), and as in the case of agrochemicals, some truck and tractor manufacturers made the vehicles or engines in Argentina and export them to other locations worldwide. This is the reason the consumption was checked to be similar. The local transport company reported diesel consumption 28% larger when trucks drive on mountain roads of the region [24]. The average driving on the plains and on the mountains lead to 0.65 MJ/tonne km,

Table 1
Energy and carbon footprint of selected fuels and materials used in the present work.

	Unit	Energy/unit	GHG/unit
Diesel	Litre (L)	40[a] MJ/L	0.075[b] kg CO_2/MJ
Herbicide	kg active ingredient	418[c] MJ/kg herb.	
Herbicide	kg active ingredient		23[d] kg CO_2/kg herb.
Fertiliser N manufacturing	kg N	41[e] MJ/kg N	7.2[e] kg CO_2/kg N
Fertiliser N emissions from soil	kg N		4.2[f] kg CO_2/kg N
Fertiliser P manufacturing	kg P	19[e] MJ/kg P	1.2[e] kg CO_2/kg P
Human labour	h	10.6[g] MJ/h	0.88[g] kg CO_2/h
40-tonne truck long distance	Tonne km	0.65[h] MJ/tonne km	0.049[b] kg CO_2/tonne km
10-tonne truck short distance mountain	Tonne km	2.8[i] MJ/tonne km	0.22[b] kg CO_2/tonne km
Concrete blocks 0.2 m × 0.2 m × 0.4 m	Unit	15[j] MJ/unit	0.84[k] kg CO_2/unit
Fired bricks 0.23 m × 0.11 m × 0.07 m	Unit	4.2[j] MJ/unit	0.24[k] kg CO_2/unit

[a] Ref. [25] includes refinery.
[b] Emission factor from Ref. [22].
[c] Ref. [17].
[d] Ref. [26].
[e] Ref. [27] includes N_2O and CH_4 emissions in manufacturing.
[f] Ref. [23] N_2O emissions in agricultural soils due to fertilisation.
[g] Section 2.3 of the present work.
[h] Average driving highways in the plains and in mountain Ref. [24].
[i] Local truck driving on mountains, energy from Ref. [25] times 1.28 Ref. [24].
[j] Ref. [28].
[k] Assuming regional conditions cement and bricks are fired with gas Ref. [22].

which is close to the truck fuel consumption of 0.63 MJ/tonne km reported for EU [25]. GHG emissions were obtained assuming diesel is the fuel consumed [22].

In Table 1, energy and GHG emissions for different inputs are depicted, and sources listed below. Together with data for primary fuels and agricultural inputs, the energy and carbon footprints to manufacture concrete blocks and fired bricks were included.

Not having local data on footprint for bricks and concrete blocks (10% cement), published results by Venkatarama and Jagadish [28] are assumed as manufacturing embodied energy; although CO_2 embodied were calculated with the emission factor of gas [22], which is regionally the main fuel for cement and bricks manufacturing in Argentina.

Although the present work focuses on a particular regional South American case study, life cycle inventory assessments can be extended to other regions/customs simply by setting the particular input values required elsewhere. When possible, this focus on local conditions is suggested as a more accurate evaluation method (*Tier 2* methodology) by the IPCC [22].

3. Results and discussion

3.1. Energy and GHG emissions in the production of straw

Table 2 summarises energy and GHG footprints for each input in the production of wheat straw. The farm inputs are multiplied by the energy/emission factors given in Table 1. Seed is estimated by loop calculation, i.e. the impact obtained per kg of grain is used as impact for seed and a new total is obtained, until the difference between consecutive loops is less than 5%. In this case only one loop was needed. GHG emissions from N fertilisation include soil emissions of N_2O derived from applying fertiliser. Labour comprises all activities from sowing to harvesting grain and baling.

The result per kg of only grain assumes all grain is harvested and all straw is left on ground. The result per kg grain and straw assumes all grain is harvested and half the straw is baled. Since for the purpose of construction material straw is not a residue but a valuable resource, a mass criteria for allocating equal impacts to grain and straw was used. Economic allocation would give a similar result in the present case, as the farmer sells most bales produced for construction at a weight price similar to grain. Bales weight in average 10 kg each. Half of the straw produced is left on ground. This will be explained in detail below when soil sustainability is discussed.

Main energy footprints to obtain straw correspond to diesel combustion on site, followed by the manufacturing of agrochemicals. Carbon footprint looks different: relative impacts for agrochemicals are slightly higher than for fuels. This is due to emissions from agricultural soils under fertilisation, which occur either with synthetic fertiliser (as considered here), or by using manure [23]. Agriculture non-CO_2 emissions were in the present case mainly N_2O derived from application of fertiliser. The impact of labour is a minor contributor for straw bale production, as well as the seed required.

3.2. Energy and GHG emissions in the manufacturing of blocks

In Section 2.1, the construction system with straw-clay blocks was described. In Table 3, materials, fuels, and labour required

Table 2
Energy and GHGs for machinery and inputs to obtain wheat grain and straw.

		Energy (MJ/ha)	Percentage energy	GHGs (CO_2e/ha)	Percentage GHGs (%)
Seed	150 kg/ha	180	4%	18	5
Diesel	56 L	2240	54%	168	44
Herbicide	1.6 kg/ha	669	16%	37	9.5
N Fertiliser	10 kg N/ha	410	22%	114	38
P Fertiliser	25 kg P/ha	475		30	
Labour	16 hs/ha	169	4%	14	3.5
Total per ha		4143		381	
Grain production	3000 kg/ha	1.2 MJ/kg grain	0.11 kg CO_2/kg grain		
Grain and 50% straw extracted	4500 kg/ha	0.92 MJ/kg grain and straw	0.085 kg CO_2/kg grain and straw		
Straw bale, size 0.35 m × 0.45 m × 0.90 m	150 bales/ha	9.2 MJ/bale	0.84 kg CO_2/bale		

Table 3
Energy and CO_2 footprints of straw-clay blocks manufactured at the construction site.

	Inputs for 1000 blocks	Energy (MJ)	Percentage of energy (%)	GHG (kg CO_2e)	Percentage of GHG (%)
Cereal straw	1800 kg	1657	29	152	32
Straw transport	20 km × 2 trips	450	16	35	15
Clay transport	4 m^3, 40 km	450		35	
Gasoline	12 L	588	10	42	9
Human labour	240 hs	2535	45	210	44
	Total	5681		474	
Footprint for each straw-clay block on construction site	5.68 MJ/block	0.47 kg CO_2e/block			

to manufacture the blocks is depicted, along with the energy and carbon footprint obtained for each input. As mentioned, data were obtained from professional work in a small size local enterprise. The manufacturing of 1000 straw-clay blocks of 0.21 m × 0.25 m × 0.50 m requires the use of 4 m^3 of dry clay, 180 straw bales transported 20 km to the construction site, 12 l of gasoline and 240 h of labour. The available 10-tonne truck can load 105 bales, so 2 trips are required for the 20 km from the farm to the construction site. Bales are low density and imply large volumes to transport. Clay is obtained from a location 20–40 km away depending on construction site, and it is transported by a 10-tonne truck. Here a distance of 40 km is assumed to include all construction sites carry on so far. The energy and GHGs for clay given in Table 3 are only the transport from mine to the construction site. Gasoline is used in the drum mixer. Specific footprints for human labour and for obtaining straw were given above.

To manufacture the blocks at the construction site, human labour was the major impact, followed by the provision of straw. For the present case study, labour has the largest energy and carbon footprints, which was intuitively suspected at the beginning of the research. Nevertheless, it is interesting to observe that labour is a minor contributor to straw bale production, and in fact the absolute footprint of straw is relatively low. This is due to the allocation to grain, but it corresponds to reality because no straw is produced without grain, except for some accidental or failed harvest. Transports of clay and straw have slightly higher footprints than fuel used in the mixer.

3.3. *Comparison of different wall materials*

In this section, energy and carbon footprint of straw bales and straw-clay blocks required for 1 m^2 of wall will be compared with fired bricks and concrete blocks. The transport from the manufacturing location to the construction site was also added assuming regional conditions as explained in 2.4. This implies 700 km of transport, which adds 1.4 MJ/brick and 0.11 kg CO_2e/brick. Concrete blocks are manufactured locally with local sand and 10% cement and then only the transport of cement was added to the values on Table 1. In Table 4, five options of wall elements are depicted. The number of elements to cover 1 m^2 of wall is shown in the first column, and in all cases neither the mortar nor the plasters were included.

The options using straw showed the lowest energy and carbon footprint per m^2, being the differences very significant compared with fired bricks and concrete blocks. Therefore, on one hand, the footprint of the construction stage with straw should be smaller, and on the other hand, due to better thermal conductivity, the operational footprint should also be significantly smaller. In the region of study there exist various solutions to resolve the low thermal conductivity of bricks and cement blocks, i.e. insulation materials like glass wool or polystyrene are available in the local market. However, the application of these solutions to current buildings is very rare [12], and buildings are instead equipped with large power gas heaters to compensate for inefficiencies. This situation is largely possible due to low gas prices, but it implies high environmental and social risks [15].

In Table 4, the best thermal performance with low footprints is achieved by using whole straw bales. However, this option requires more land for cultivation to satisfy the demand. For instance, to cover an envelope of 140 m^2 (a typical one-family house of 120 m^2 living area), straw bales would require the use of 420 bales and 2.8 ha of cultivation; while covering the same envelope with straw-clay blocks would demand 980 blocks and 1.2 ha. For the same building, an envelope made with whole straw bales will require more than double land cultivated area than when using blocks. On the other hand, the option with straw bales has better thermal conductivity, although, in comparison with the majority of conventional buildings in the region, straw-clay walls have 3–4 times better thermal insulation. The choice for one of the systems should be made considering several variables: climate, straw and clay availability, and energy options for heating.

If straw bales were not local, transportation could add large footprints due to low-density bales and trucks filled with small weight but large volume. For instance, a large truck as considered above for long distance can fit 500 bales, and if delivered from 700 km there would be transport energy embodied per bale of c.27 MJ/bale. This footprint would favour an option of straw-clay blocks instead, as the resulting embodied energies per m^2 wall would be 75 MJ for straw-clay block and 109 for whole bales. However, this long distance bale delivering would anyway result in smaller impacts for straw options than for fired bricks and concrete blocks. The option using half bales is interesting from both, land requirement and possible long distance delivery. Half-bale walls result in better thermal resistance than straw-clay blocks and require 1.4 ha to cover the same wall surface of 140 m^2 discussed above. Some pilot constructions have been done in the region of study, and Figs. 5 and 6 show

Fig. 5. Half-bale setting with wooden frames.

Table 4
Energy and carbon footprint for a number of elements to cover 1 m^2 of wall.

Number required per m^2 of wall	Thermal conductivity (W/m K)	Thermal transmittance (W/m K)	Energy per m^2 wall (MJ/m^2)	GHG emissions per m^2 wall (kg CO_2/m^2)
85 Fired bricks	0.90[a]	3.9	488[b]	30
11 Concrete blocks	0.64[a]	3.2	169[c]	9.6
7 Straw-clay blocks	0.18[d]	0.86	40	3.4
3 Straw bales	0.07[d]	0.16	28	2.5
3 Half straw bales	0.07[d]	0.32	14	1.3

[a] Ref. [29].
[b] Includes 700 km transport.
[c] Includes 700 km transport in 10% of weight due to cement.
[d] Ref. [9].

a small building of 11 m^2 dedicated to a machine shop at the wheat farmers land.

Half-bales were obtained from whole bales by cutting with a chainsaw, and were not easy to handle without crumbling apart. Therefore a system of modular prefabricated wooden frames with half-bales attached was design [8]. Half-bales were fast to the frames on a horizontal plane, and then the frames set up in the pilot construction shown in Figs. 5 and 6. For this particular pilot construction, the technique proved to be simple and of fast accomplishment.

Straw bale and straw-clay walls need to have moisture protection from both sources, inside ambient and outdoors. In the constructions already made in the region, plasters were preferred, and a water-proof finishing layer added. The finishing is done with a mix of fine grain sand, clay, and the addition of flax oil, and a variety of water proof paints. Besides, walls are set either on concrete or on stones bound with sand and cement mortars to avoid moisture reaching upwards. Other authors have reported on moisture management and measurements on straw walls. Goodhew et al. [30] summarised moisture management in straw walls, and developed techniques for monitoring. In the buildings studied by these authors the level of moisture was found below 20%, in agreement with the work of Ashour et al. [6]. The thermal properties of the mix of straw and clay used for the blocks in the present work were previously investigated by Goodhew and Griffiths [9], but durability was not reported. Problems of moisture penetration, plaster stability, and long-term durability should be addressed in future works to make a complete comparison of different types of finished walls.

3.4. Sustainability issues and carbon sequestration

As mentioned, the extraction of straw from the cultivation field cannot be 100%. Several authors showed that crop reside removal from fields can lead to soil degradation by decreasing soil organic carbon [31]. Depending on soil and climate a minimum around 50% to 70% of straw should be left on ground to maintain the amount of organic carbon stable in agricultural soils under no tillage practices. On the other hand, a significant contribution to organic matter in soils is obtained from the roots. In a following up experiment of 54 years, Kätterer et al. [32] concluded that roots undisturbed by no tillage contribute as much organic matter to agricultural soils as residues like straw. Both actions were followed by the farming operation surveyed, where straw is cut at a chosen height when the grain is harvested. The farmer reported that in the past, for a period of 3 years, by pressure from various ongoing constructions they were harvesting almost all straw from wheat and rye fields, and found degradation of soil and lower productivity. The farmer reported that after the experience only 50% of the straw was taking away, and with this rate of removal they observed no changes in soil conditions and productivity. This might not be valid for cultivation elsewhere.

Fig. 6. Half-bale walls with plaster.

Agricultural products capture carbon from the atmosphere, in both the part harvested and in soils. The carbon captured by wood or straw is usually not counted as sequestered from the atmosphere because it might return by degradation. However, carbon captured by soils could be considered as permanent sequestration. Estimating carbon capture by soils is complex, and depends upon a large number of variables according to climate, locations and farming practices. Global estimates for potential sequestration in croplands are c.2200 kg CO_2/ha [31], which would imply for each straw bale a sequestration of −3.6 kg CO_2. As a consequence, 1 m^2 of straw-bale wall would be a carbon sink of −8.3 kg CO_2, while for straw-clay blocks the resulting emissions would also be a sink of −1.2 kg CO_2. These results lead to a larger difference in footprints with respect to fired bricks and concrete blocks (Table 4). It is out of the scope of the present work to deepen into carbon captured; although other estimates on particular croplands give even larger sequestration potential than the global values used here. In any case, it is clear that by using wood and agricultural products, whether directly or included in construction elements, the building sector has a high potential for reducing impacts, and even capturing a significant amount of CO_2.

4. Conclusions

Energy and carbon footprints in the use of cereal straw as renewable resource for envelope walls were investigated for local conditions in the Andean Patagonia. Straw is obtained from local farmers in no-tillage low-input agriculture. A maximum of 50% straw should be harvested in order to guarantee soil organic carbon content and fertility. Under these requirements, 1500 kg of straw per ha can be obtained sustainably, which can be used as whole bales to cover 50 m^2 of wall per ha, or 100 m^2/ha if half bales were used. This last option led to walls with 22 cm thickness of straw, but double thermal transmittance. On the other hand, local manufacturing of straw-clay blocks was studied in detail. This is an option that allows covering a wall surface of 120 m^2 per ha cropland, although doubling thermal transmittance with respect to the half bale option. The three straw solutions investigated have much better thermal performance than fired bricks or concrete blocks, which are at present the most common wall envelopes in the region of study.

A comparison with fired bricks and concrete blocks, the two most common wall materials used in the region, showed that straw solutions embodied much less energy and carbon footprints per m^2 of wall. Embodied energies and CO_2 of 28 MJ and 2.5 kg CO_2e per m^2 wall covered with straw bale, and 40 MJ and 3.4 kg CO_2e per m^2 wall covered with straw-clay blocks were found, respectively. These footprints are much smaller than for common fired bricks (481 MJ/m^2 wall, 38 kg CO_2e/m^2 wall) and concrete blocks (141 MJ/m^2 wall, 11 kg CO_2e/m^2 wall). Concrete blocks are manufactured locally but include cement from 700 km away. The straw options can even become a carbon sink under certain conditions of agricultural soils. At present, thermal insulation in buildings is rare in the region interested to this work, and very large consumption of energy in heating is found. The inclusion of straw solutions in the very cold region of Andean Patagonia will not only lower energy and carbon footprints per m^2 of wall, as discussed here, but would also improve operative energy use in buildings.

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