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RESEARCH

Techno-economic impact assessment of recycled gypsum usage in plasterboard manufacturing

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Abstract

Recycled gypsum derived from post-consumer sources is a promising resource that can be reincorporated in the production chain, offering opportunities to decrease manufacturing costs given its significantly lower price compared to conventional gypsum. The systematic usage of post-consumer recycled gypsum is a relatively new practice in the plasterboard industry and there is lack of extensive literature references on the potential effects on the manufacturig process, since the available related studies are limited to more holistic approaches. The current work is, to our knowledge, the first study to assess the practice of gypsum recycling from an economical and technical point of view within the boundaries of the plasterboard manufacturing process. The paper provides a detailed techno-economic impact assessment of the usage of recycled gypsum up to 30% by weight in feedstock in the manufacturing of Type A plasterboard, based on data collected from full-scale industrial production trials carried out in five representative European plants located in four different countries. The potential impacts are analyzed in relation to each affected process parameter. A series of options for process adjustments, modifications and corrective measures in order to amortize the effects on product quality and/or cost are also reported. The analysis indicates high dependence of the cost impacts on process-specific characteristics. A limited reduction of 0.6% in the average total manufacturing cost per m^2 of plasterboard was calculated, which can be associated to the considerable decrease, by 9.5%, of raw material costs. The latter fully compensates the increases to other process costs, and mainly to chemical additives which increased by 8%. The overall analysis allows quantification of the process parameters and costs that are affected when the percentage of recycled gypsum incorporated in plasterboard production is significantly increased. The results and the methodology proposed in the study can serve as a basis for a representative cost impact assessment of high-percentage recycled gypsum incorporation in any typical plasterboard production line plant. The methodology can serve as a guideline for techno-economic assessment of industrial production lines where the input datasets originate from different plants and can be characterized as "non-homogeneous" due to case-specific differences.

Keywords Recycled gypsum · Plasterboard manufacturing process · Techno-economic impact · Plasterboard manufacturing costs

Introduction

Recycling of construction materials is considered highly important, since the construction industry is the most material resource intensive economic sector in the EU [1, 2]. Post-consumer recycled gypsum (i.e. derived from gypsum waste from construction, renovation, deconstruction and demolition activities) is a promising resource that can be reincorporated into the production chain.

Gypsum recycling is prompted by current EU legislation, primarily by the Waste Framework Directive 2008/98/EC [3] that highly discourages waste disposal and places it as the last option according to the established waste hierarchy. Moreover, the landfilling of gypsum waste has been linked with potential H_2S emissions, which is a hazardous, toxic at high concentrations, and flammable gas with environmental and health effects, and odor problems [4–6]. Council Decision 2003/33/EC [7] states that "non-hazardous gypsum-based material should be disposed of only in landfills for non-hazardous waste in cells where no biodegradable waste is accepted".

As a result of this legislative framework, especially the imposed disposal of these wastes in mono-cells, the respective landfill gate-fees have raised considerably in many Member States [8], thus making the recycling option more economically attractive for all stakeholders involved. Gypsum waste can be separated on site and forwarded to specialized recycler companies that process it to produce recycled gypsum. The cost of dismantling, sorting, collecting, transporting and recycling of the waste can be kept well below the cost of the landfilling alternative [9].

The systematic usage of post-consumer recycled gypsum is a relatively new practice in the plasterboard industry and there is lack of extensive literature references on the potential effects on the manufacturing process. So far most of the available related studies are limited to more holistic approaches, such as Life-cycle Assessment (i.e. LCA), and generally differ in scope. As seen in Table 1, a more focused investigation strictly on the plasterboard manufacturing process itself can provide useful insight regarding incorporation issues compared to a broader scope of analysis.

The current work investigates the impacts of recycled gypsum incorporation into the process in terms of manufacturing costs within the production plant boundaries, focusing on technical issues while accounting for typical particularities found among standard plasterboard production lines/plants. The proposed high recycling strategies serve natural resources preservation, increase sustainability and reduce the gypsum waste volumes that end up in landfill and the respective environmental impact arising from its improper landfilling. The paper provides a detailed techno-economic impact assessment of the high level usage of recycled gypsum up to a technically feasible maximum in Type A plasterboard manufacturing, based on data specifically collected for the study's purpose from full-scale industrial trials carried out in five representative European plants with typical plasterboard production lines, located in four different countries. The potential impacts are analyzed in relation to each individual parameter that may be affected by the introduction or increase of recycled gypsum usage in the process and a series of options for process adjustments, modifications and corrective measures in order to amortize the effects on product quality and/or cost are also reported. The structure of the study conducted in the framework of GtoG project [13] is illustrated in Fig. 1. To our knowledge, this is the first study to assess the practice of gypsum recycling from an economical and technical point of view within the strict limits of the plasterboard manufacturing process, employing actual industrial production data.

Table 1 Comparative review of studies related to gypsum recycling in Type A plasterboard manufacturing – Recycled content refers to production and post-consumer recycled gypsum in total

Scope	Area of study	Investigated scenarios	Main results	Literature source
Cradle-to-grave LCA	UK	Base – 10.5% recycled content (current average in 2007) 15% recycled content 25% recycled content	- Some environmental benefits of recycling from avoiding landfilling and production from conventional sources - Benefits found small in comparison to overall system impacts (manufacturing and distribution)	[10]
Cradle-to-cradle Material & Energy Flows	EU-27	Base case (2013)–5% recycled content Zero case – 0% recycled content High case −18.7% recycled content	- Insignificant variation in energy use between Base and High recycling case - Energy savings from avoiding gypsum mining and waste disposal counterbalanced by increased energy flows for waste and recycled gypsum transportation and for raw material pre-processing during manufacturing	[11]
Manufacturing process – Energy Analysis	Germany, France, UK and Belgium	Base (2015) – 10.9% recycled content (average) High – 25.2% recycled content (average)	- Negligible impact on total energy consumption on average level - More notable effects on individual cases with high dependence on process-specific characteristics	[12]

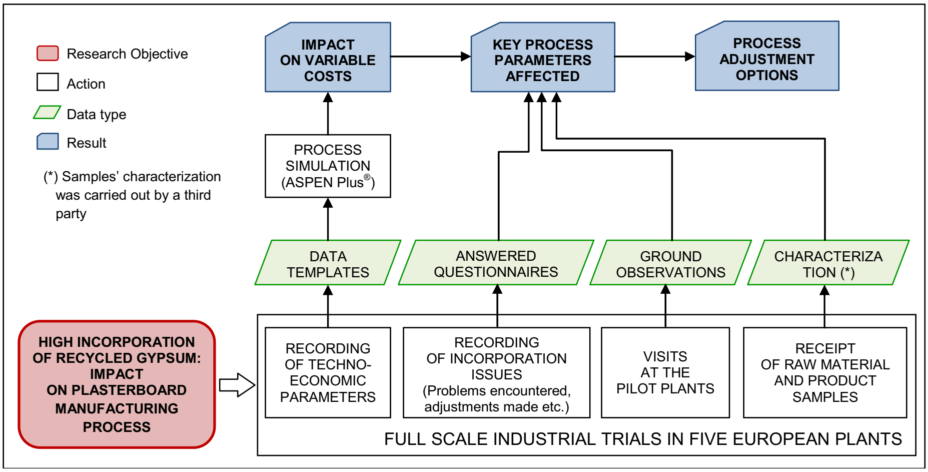

Fig. 1 Summary of the study conducted; objective, methodology, data collected, results

Plasterboard manufacturing process

Gypsum plasterboards are manufactured in a two-step process (Fig. 2). The first step's generic stages include pre-processing of the gypsum feedstock (potential size reduction and pre-drying depending on feedstock type and properties), followed by calcination. In the plasterboard industry calcination refers to the thermal processing of gypsum to change the hydration state of its dihydrate content ($CaSO_4.2H_2O$) in order to produce the intermediate product called "stucco", according to the equation:

$$CaSO_4.2H_2O + \text{energy} \rightarrow CaSO_4.1/2H_2O + 3/2H_2O$$

In practice, due to the "sensitive" setting of the chemical balances involved and to the inability to heat all the particles of gypsum uniformly, the industrially produced stucco is a mixture of calcium sulphate in varying states of dehydration [14–16].

The feedstock for the production of stucco may consist of one or more types of gypsum from conventional sources (natural and/or synthetic). It can also contain a percentage of recycled gypsum derived from pre-consumer and/or post-consumer gypsum waste. Naturally, when a feedstock mix of natural, FGD and/or recycled gypsum is used, each raw material is introduced in the process at the appropriate point (Fig. 2). The stucco production step may involve a series of equipment units (i.e. crushers, dryers, mills, heated mills, calciners etc.) or modern single units for simultaneous grinding, pre-drying and calcination. Depending on the calciner design, calcination may take place by direct or indirect contact of gypsum with hot gases.

In the second step of the process, plasterboards are produced on large highly automated board lines in continuous operation. Stucco is mixed with water and a series of solid and liquid additives in specific ratios which constitute the recipe, and forms the plaster slurry. Water is added in considerable excess of the stoichiometric amount for complete rehydration of stucco back to gypsum, in order to achieve proper consistency and fluidity of the slurry. The slurry is fed to the board line where it is encased between two layers of special strong paper and, as the hemihydrate contained in stucco converts back into interlocking dihydrate crystals, it gradually sets while it is conveyed along the line at an appropriate speed. The rehydration reaction is the reverse of

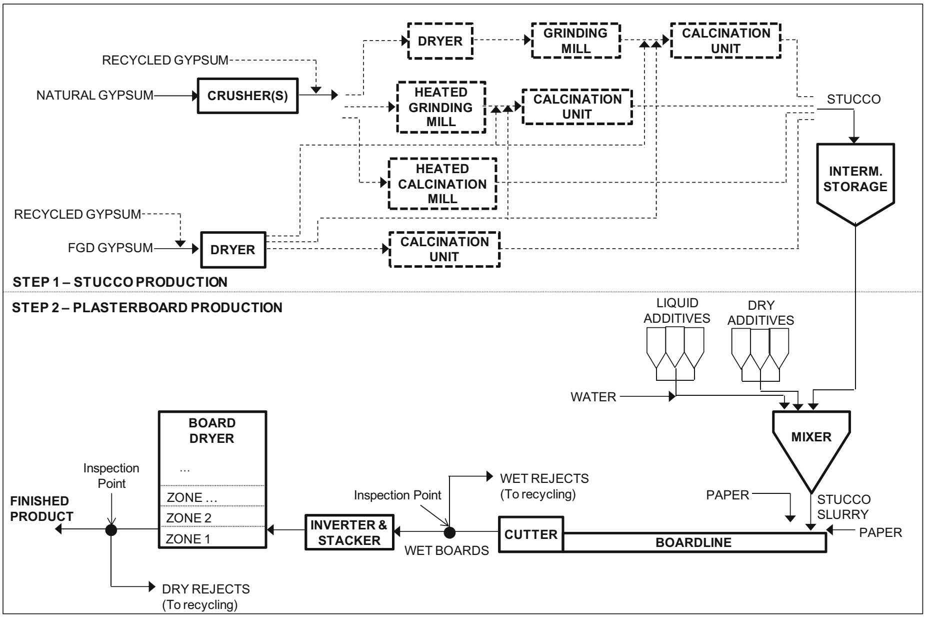

Fig. 2 Process flow of plasterboard manufacturing – Different options for the stucco production step shown in dashed lines

calcination. When set, the continuous sheet of plasterboard is cut to individual uniformly sized boards, which proceed to a large multi-deck drying kiln where the excess water added at mixing is evaporated, and exit as the finished product. Boards that are out of specifications (i.e. off-spec boards) are diverted from the process at inspection points along the line (Fig. 2).

Recycled gypsum incorporation issues and role of impurities

The gypsum products sector is one of the few fully integrated industries in the construction materials field, covering the whole life-cycle of the product; the companies which extract the mineral gypsum also process it and manufacture the value-added products and systems. Gypsum is known to be indefinitely and 100% recyclable as it always keeps its natural properties during use and it is in fact amongst the few construction materials where "closed loop" recycling is possible, i.e. gypsum waste can be used to reproduce the same product [17].

Regarding plasterboard manufacturing in particular, post-consumer recycled gypsum is offered at significantly lower prices than conventional raw materials or even often at zero cost to the manufacturers. Therefore, the incorporation of recycled gypsum into production is a potential means to address the on-going necessity for lower manufacturing costs, especially in the face of the dramatic effect of the global financial crisis on the construction sector.

Consequently, recycled gypsum constitutes the third increasingly used source of gypsum as a raw material, together with the two main types of conventional gypsum, i.e. natural and synthetic FGD gypsum. Until now, most plasterboard plants have been recycling their own production waste, which results in up to ~5% by weight inclusion of re-processed gypsum in feedstock (i.e. pre-consumer recycled gypsum). Recently, some plants have started to introduce post-consumer recycled gypsum, reaching incorporation rates of recycled material in feedstock up to 10–15% by weight. The main market constraints to the spread of recycled gypsum are the potentially uncertain quality of the recycled material that may hinder its use due to technical reasons, and the availability of sufficient volumes to meet production needs on a constant basis. Regarding the latter, estimates of the amounts of generated gypsum waste are generally scarce. This is partly due to the fact that buildings are currently mostly demolished rather than dismantled in the majority of the Member States, making the sorting and quantification of the waste impractical. An estimation of 1.9 million tonnes of post-consumer plasterboard waste generated in the EU-27 for the year 2013 is reported by Jiménez Rivero et al. [11]. However, given that construction and demolition wastes are by far the largest waste stream in Europe [2] and considering the widespread usage of plasterboard in modern constructions, post consumer gypsum waste volumes are expected to become increasingly larger in the future. Still, it is necessary to achieve pure recycled gypsum of high and consistent quality, as free as possible of the impurities arising from its post-consumer origin, so that it can be systematically incorporated at high rates into the manufacturing process of gypsum products without problems.

Recycled gypsum is introduced into the manufacturing process in a controlled blend as one single stream and not as separate streams depending on its sources (i.e. pre- and/or post-consumer). The handling and pre-processing of the material depends on its quality characteristics.

Recycled gypsum is usually in the form of a fine or sandy powder, or a small aggregate-type material [10]. Its particle size distribution differs from both natural and FGD gypsum. Its moisture content can vary broadly, depending on the wet/dry production rejects ratio, the handling conditions at the jobsites where the post-consumer waste originate from, as well as the storage and handling conditions of the waste and/or the recycled gypsum by the gypsum recyclers [18]. Purity ($CaSO_4.2H_2O$ % *w/w* content on a dry basis) constitutes the most important quality index of gypsum as a raw material; high purity of feedstock results in the production of lower weight plasterboard [19]. The purity of recycled gypsum, although usually within acceptable ranges, is typically lower compared to conventional gypsum.

In general, the quality requirements set by the manufacturers as to these basic attributes of recycled gypsum tend to be based on the respective characteristics of the conventional feedstock used in each plant, in order to avoid considerable changes on the quality of the feedstock mix and additional pre-processing of the recycled material. As a reference, natural gypsum rocks normally contain 1–3% free moisture when extracted and their degree of purity is typically around 80%, but can vary between 75 and 95%, depending on the deposit. FGD is a wet material (around 8–10% moisture content) of considerably higher purity (over 95%) in finely grained powder form [10, 16, 19, 20].

The types and amounts of impurities present in recycled gypsum may vary depending on the waste sources from which it is derived and the resulting process effects may differ considerably in nature, in their stage of occurrence, as well as in importance. Many of the bottlenecks that hinder the reincorporation of recycled gypsum into plasterboard manufacturing, especially as it increases to further higher levels, primarily relate to the presence of certain impurities in the material, which essentially constitute important quality indexes. In this respect, residual paper and fibres from recycled plasterboard waste are one of the major limiting factors of the threshold reincorporation percentages.

The recycling of pre-consumer gypsum waste usually takes place directly at the manufacturing plant, although some manufacturers send their waste to external recyclers [8, 10]. The volume of this waste is generally low and its incorporation in the process has minimal impact. Hence, in-plant plasterboard recycling facilities have low paper removal capacity or even completely lack paper removal.

Post-consumer recycled gypsum received in powder form from external recyclers contains some residual paper and cellulose (i.e. paper and wood) fibres, typically <1.5% (in total, expressed as TOC, i.e. Total Organic Carbon) according to most existing specifications [8, 21, 22]. Potential process effects relate not only to the amount of paper but also to the size of paper flakes which can cause equipment blockages.

Common impurities in conventional gypsum, both natural and synthetic, are chloride, magnesium, sodium and potassium salts, referred to as water soluble salts. These salts readily dissolve when stucco is mixed with water and during the drying of the plasterboard they migrate to the paper – core interface and interrupt the bond [19]. Even though their presence in feedstock is not particularly linked with the use of recycled gypsum, relatively higher salt contents potentially found in the material could be related to residual paper, and in such case the increased use of recycled gypsum could negatively affect product quality.

Silicones arise from the additives contained in the plasterboard core, mainly in case where special technical boards (e.g. water-resistant plasterboard waste) are included in the recycling process [23], from certain physical impurities related to the post-consumer origin of recycled gypsum (e.g. ceramic tiles) and, to a lesser extent, from the glue used in the board's edges. Their presence is undesirable, because of their hydrophobic nature; they act as water-repellant agents in stucco, increasing excess water demand in the slurry mixer and impact the wetting process and the activity of certain additives (e.g. foaming agents), thus causing variability in water absorbance and disruption of the board core structure [19, 23].

The quality requirements for post-consumer recycled gypsum regarding the basic attributes described above and the maximum acceptable content of impurities and other toxicological parameters (i.e. heavy metals, etc.) are currently defined either by national specifications that have been issued in some European countries, or by individual commercial agreements between manufacturers and recyclers, the latter being mostly the case [8]. In general, the consistency of quality characteristics between the different loads of recycled material regularly received at a plant is considered an important factor.

Methodology

The general methodology and the types of data employed in the present techno-economic impact assessment are shown in Fig. 1. The data were obtained from two rounds of full-scale industrial production trials that took place from January 2014 until March 2015 in five plasterboard manufacturing plants located in Germany, France (2 plants), the UK and Belgium. The selection of five of the most representative plants in Europe in terms of process variations, capacity and raw material mix, and the fact that the industrial partners of GtoG project are among the top leaders in the gypsum industry covering most of the European market share, allows generalization of the methodology and the global results. The trials were carried out in two parts. The 1st round of trials refers to a series of runs of the standard production in each plant and serves as base scenario. The 2nd round involves repeated test productions with gradual increase of the amount of post-consumer recycled gypsum above the current standard (if any) amount used, up to a technically feasible maximum, with a maximum set target of 30%

by weight recycled gypsum in total (pre- and post-consumer). All plants use typical production lines, but the processes are not identical; differences exist in the feedstock/feedstock mix used and consequently in the raw material pre-processing stages, as well as in the types of industrial equipment employed (e.g. single-unit calcination as opposed to set-ups of dryers and/or heated mills and calciners). It is noted that the technically feasible maximum achieved in each plant in the 2nd round of trials was defined either by product quality and/or process efficiency.

Outline – Formation of a generic process model

The study specifically focuses on the manufacturing process of standard plasterboard (Type A) and its scope is therefore defined to include all operations from the entrance of the manufacturing plant to the production of the finished plasterboard. Further upstream and downstream operations (e.g. raw material production, product packaging etc.) do not fall into the scope of study, since their respective costs remain unaffected by the introduction of recycled gypsum in the process. For the same reason, labor costs are also excluded.

The transportation of raw materials from their source to the plasterboard plant is typically the responsibility of a third party (raw material supplier, gypsum recycler). There are cases however, such as the transfer of natural gypsum from the quarry to the plant, where it can be carried out by the plasterboard manufacturer (i.e. with trucks owned by the plant).

Regarding recycling, there are different practices applied among the plants studied that include the following:

- The plasterboard waste generated from production may be either processed at in-plant recycling facilities (i.e. internal recycling) or sent to be recycled by a third party (i.e. external recycling).
- Recycled gypsum is typically received by an external supplier (recycling company).
- Alternatively, post-consumer gypsum waste may be received by the plant and be processed internally at the in-plant recycling line together with pre-consumer waste from production.

A generic process model is thus formulated limited within the manufacturing unit's borders (Fig. 3), intending to cover all possible routes that may be followed by a plant in relation to the handling of recycled gypsum and/or gypsum waste. The functional unit is 1 m^2 of Type A plasterboard (12.5 mm thickness).

Calculations

The costs that vary depending on production output are defined as variable costs. The direct costs affected by the incorporation of recycled gypsum in the plasterboard manufacturing process are hereon referred to as variable (plasterboard) manufacturing costs and include raw materials, paper, additives, water, fuel and electrical energy per unit (i.e. 1 m^2) of plasterboard produced.

The impact of the high-level usage of recycled gypsum on the variable costs of Type A plasterboard manufacturing is calculated based on a set of technical and economic parameters systematically recorded during the production trials. The recorded parameters include the feedstock composition and its basic characteristics (i.e. free moisture content, purity, main impurities) and all incoming material and energy flows as well as their respective unit costs according to the described generic model (Fig. 3). ASPEN Plus® 2006 [24] was used to simulate each production process at each of the five investigated plants, taking into account the

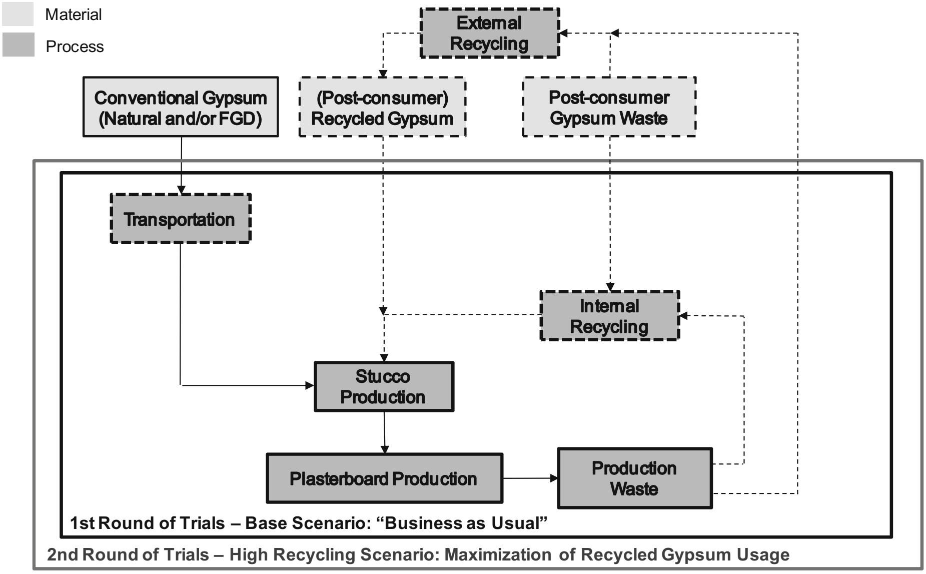

Fig. 3 Generic process model for plasterboard manufacturing – Standard practices followed by all five examined plants shown in solid lines, case-specific practices in dashed lines

particular processing activities and equipment sequences, in order to perform the mass and energy balance calculations.

The reported recycled gypsum incorporation rates refer to the total amount of recycled material (i.e. pre- and post-consumer) included in the feedstock mix, expressed as weight percentage on a wet basis.

In order to include all costs within the study’s scope per m^2 of plasterboard in a consistent manner for all five sample plants, calculations are based on the following:

- Raw material transportation costs are taken into account built-in in their unit price whether transportation is carried out by a third party or by the manufacturer.
- In case the recycling of post-consumer gypsum waste is carried out by the plant (i.e. internally), the respective cost is taken into account and is built-in in the net unit cost of recycled gypsum.
- The recycling cost of pre-consumer waste is calculated based on production yield only when processing takes place in internal recycling lines. If this waste is recycled by a third party the respective cost is already built-in in the net unit cost of recycled gypsum sold back to the manufacturers.

In addition, the rate of conversion of the feedstock’s dihydrate content into hemihydrate in calcination is assumed 100%, as suggested by the manufacturers.

The actual production data as well as the individual results from each of the five plants regarding the impact of the maximized incorporation of recycled gypsum powder are subject to commercial confidentiality. Therefore, the assessment results are presented in the form of percentage variations.

Due to these confidentiality related limitations, two generalized scenarios (one for each round of trials) are developed as shown in Table 2, based on the actual data from each of the five plants. The methodology of the calculations is outlined in Table 3 (Method 1). For the present assessment it is $m = 5$ and $j = 6$, where the elements j are the variable plasterboard manufacturing costs listed in the beginning of this section. The consumptions c_{ij} were calculated from the mass and energy balances in ASPEN Plus® 2006 based on the specific sets of inputs as recorded in the trials. Unit costs were provided by each plant separately for each raw material (i.e. natural gypsum, FGD and recycled gypsum) and the respective p_{ij} and p'_{ij} for raw materials in total were calculated accordingly. For the remaining variable cost elements, unit costs were provided in the datasets as is, and they are invariable in both generalized scenarios (i.e. $p_{ij} = p'_{ij}$).

The adoption of Method 1 was preferred over the alternative approach of Method 2 which was also considered (see Table 3), because the latter method yields rather misleading averages due to the combination of two facts. Firstly, existing process-specific differences appear to bias the effects (i.e. increase/decrease) on individual cost elements among the plants resulting from the increased incorporation of recycled gypsum. This, in conjunction with notable differences observed in the individual plant cost structures (see Table 6 in Section "Results and discussion"), causes the average impact on an element's cost to deviate from the respective average impact on the element's consumption. On the contrary, the chosen approach focuses on the essential impact on the average consumption of each cost element j, which is proportional to the respective impact on its cost in the generalized scenarios. Thus, the calculated average impacts I_j can be representative of the respective process effects.

The proposed methodology can be applied to any plasterboard manufacturing plant, as well as to similar industrial production lines, and can serve as a guideline for techno-economic impact assessments where the input datasets originate from different plants and can be characterized as "non-homogeneous" due to case-specific differences.

The effect of recycled gypsum usage on cost is also assessed for each of the two distinct main steps of the plasterboard manufacturing process, as shown in Table 4, namely Stucco Production and Plasterboard Production. The separate assessment of the impact on stucco production is considered important, since stucco is an intermediate product that can be used in the manufacturing of a series of gypsum products in addition to plasterboard.

Results and discussion

The recycled gypsum incorporation rates per plant in the two rounds of trials are shown in Table 5. At three of the five plants relatively small percentages of post-consumer recycled gypsum were already incorporated in standard production (1st round of trials). It is, however, evident that in the 2nd round of trials the use of recycled gypsum was remarkably increased in all cases. The 30% target was reached in two out of the five plants. It should be noted that in

Table 2 Generalized scenarios developed for the assessment

Scenario	Corresponding trials	Description
Base	1st Round	Standard production – Current recycled gypsum incorporation rate in each plant
High Recycling	2nd Round	Maximum recycled gypsum incorporation rate achieved in each plant (up to the maximum set target of 30%)

Table 3 Outline and comparison of methodologies considered for the techno-economic impact assessment (for *m* number of plants, where the total cost of plasterboard per m² in each plant *i* consists of *n* cost elements *j*)

		1st round of trials		2nd round of trials	
		Method 1 (selected)	Method 2 (rejected)	Method 1 (selected)	Method 2 (rejected)
Plant *i*	Consumption of *j* per m² of board	c_{ij}	c_{ij}	c_{ij}	c_{ij}
	Unit cost of element *j*	p_{ij}	p_{ij}	p_{ij}	p_{ij}
	Cost of *j* per m² of board	$x_{ij} = c_{ij} \cdot p_{ij}$	$x_{ij} = c_{ij} \cdot p_{ij}$	$x_{ij} = c_{ij} \cdot p_{ij}$	$x_{ij} = c_{ij} \cdot p_{ij}$
	Total cost of board (per m²)	$x_i = \sum_{j=1}^{n} x_{ij}$	$x_i = \sum_{j=1}^{n} x_{ij}$	$x_i = \sum_{j=1}^{n} x_{ij}$	$x_i = \sum_{j=1}^{n} x_{ij}$
	% Impact on cost of *j*	$I_{ij} = \frac{x'_{ij} - x_{ij}}{x_{ij}} \cdot 100$	$I_{ij} = \frac{x'_{ij} - x_{ij}}{x_{ij}} \cdot 100$	$I_{ij} = \frac{x'_{ij} - x_{ij}}{x_{ij}} \cdot 100$	$I_{ij} = \frac{x'_{ij} - x_{ij}}{x_{ij}} \cdot 100$
	% Impact on total cost of board	$I_i = \frac{x'_i - x_i}{x_i} \cdot 100$	$I_i = \frac{x'_i - x_i}{x_i} \cdot 100$	$I_i = \frac{x'_i - x_i}{x_i} \cdot 100$	$I_i = \frac{x'_i - x_i}{x_i} \cdot 100$
Generalized scenarios (plants 1 to *m*)	Average consumption of *j*	$C_j = \frac{1}{m} \cdot \sum_{i=1}^{m} c_{ij}$	$C_j = \frac{1}{m} \cdot \sum_{i=1}^{m} c_{ij}$	$C'_j = \frac{1}{m} \cdot \sum_{i=1}^{m} c'_{ij}$	$C'_j = \frac{1}{m} \cdot \sum_{i=1}^{m} c'_{ij}$
	Average unit cost of *j*	$P_j = \frac{1}{m} \cdot \sum_{i=1}^{m} p_{ij}$	N/A	$P'_j = \frac{1}{m} \cdot \sum_{i=1}^{m} p'_{ij}$	N/A
	Average cost of *j* per m² of board	$X_j = C_j \cdot P_j$	$X_j = \frac{1}{m} \cdot \sum_{i=1}^{m} x_{ij}$	$X'_j = C'_j \cdot P'_j$	$X'_j = \frac{1}{m} \cdot \sum_{i=1}^{m} x'_{ij}$
	Average total cost of board (per m²)	$X = \sum_{j=1}^{n} X_j$	$X = \frac{1}{m} \cdot \sum_{i=1}^{m} x_i$	$X' = \sum_{j=1}^{n} X'_j$	$X' = \frac{1}{m} \cdot \sum_{i=1}^{m} x'_i$
	Average % impact on cost of *j* [a]	$I_j = \frac{X'_j - X_j}{X_j} \cdot 100$	$I_j = \frac{X'_j - X_j}{X_j} \cdot 100$	$I_j = \frac{X'_j - X_j}{X_j} \cdot 100$	$I_j = \frac{X'_j - X_j}{X_j} \cdot 100$
	Range of impact on cost of *j*	Range of I_{ij} values in Plants 1 to *m*			
	Average % impact on total cost of board	$I = \frac{X' - X}{X} \cdot 100$	$I = \frac{X' - X}{X} \cdot 100$	$I = \frac{X' - X}{X} \cdot 100$	$I = \frac{X' - X}{X} \cdot 100$
	Range of impact on total cost of board	Range of *I* values in Plants 1 to *m*			

[a] It is also $I_j = \frac{(C'_j - C_j)}{C_j} \cdot 100$ in the selected Method 1, but not in the rejected Method 2

Table 4 Main stages of plasterboard manufacturing as defined in the present assessment

Manufacturing stage	Included processes
Stucco production	- Raw material transportation (when applicable) - Raw material pre-processing (i.e. size reduction and pre-drying) - Calcination
Plasterboard production	- Mixing of the stucco slurry - Forming, setting and cutting of plasterboard - Drying of plasterboard - Internal recycling of the plasterboard waste generated from production

the generalized Base Scenario, the average recycled gypsum incorporation rate of 10.9% (see Table 5) is already well above the estimated EU-27 average [25].

Impact on variable costs of plasterboard manufacturing

The variable plasterboard manufacturing costs can be grouped in three basic categories; material, energy and water costs. Material costs consist of gypsum raw materials (conventional and recycled), facing paper and chemical additives, while energy costs include fuel and electricity. The conventional raw materials used in the plants under study are natural gypsum (three plants), FGD (one plant) and a mix of both (one plant). Fuel is natural gas; in one case waste fuel is used as supplement. The latter is taken into account in the calculations.

The distribution of variable costs of plasterboard manufacturing for the two generalized scenarios examined is shown in Fig. 4. Material costs are the main variable costs accounting in total for ~70% of plasterboard cost in both scenarios. Energy (about 2/3 fuel and 1/3 electricity) is the second most important cost category accounting for ~28%, while water has the lowest share of ~2.3% in the total cost for both scenarios. Figure 5 further focuses on the particular structure of material costs.

Based on Figs. 4 and 5, the key impact observed on the cost structure as a result of the higher-level incorporation of recycled gypsum into the process is a small shift of cost from raw materials to additives and, to a lesser extent, electrical energy. It should be clarified that the apparent small variations in the cost share of paper between the two trials refer only to changes in its percentage in the overall cost structure, as a result of variations caused on the remaining absolute cost elements, and not to changes in the actual cost of facing paper itself; the consumption of paper for a given plasterboard production rate in m^2 is –expectedly– independent of the use of recycled gypsum in the process. Hence, paper is from now on excluded from the impact analysis.

The impact on the average variable costs for the two generalized scenarios is shown in Fig. 6, according to which the incorporation of recycled gypsum up to a feasible maximum

Table 5 Recycled gypsum incorporation rates in the two rounds of trials

	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Generalized scenarios (average)
1st Round of trials (base scenario)	5%	8.9%	10%	10–15%	18%	10.9%
2nd Round of trials (high recycling scenario)	25.6%	19.9%	**30%**	25–**30%**	23%	25.2%

Maximum set target reached are bold significance

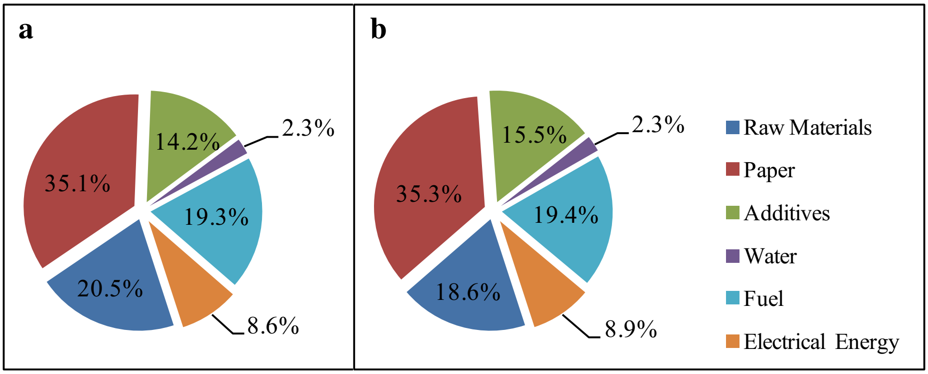

Fig. 4 Variable costs' structure of plasterboard manufacturing for the Base Scenario (**a**) and the High Recycling Scenario (**b**)

causes 0.6% decrease of the total variable cost per m^2 of plasterboard compared to the Base Scenario. The cost shift from raw materials to additives and electrical energy identified in Figs. 4 and 5 is more clearly reflected in the cost analysis of Fig. 6; the significant decrease of 9.5% in raw materials' cost fully compensates for the cost increases in other process parameters and results in the marginal decrease of total cost. Among the overweighed increases, the highest appears in additives (8%).

Figure 6 also illustrates the range of impact (highest and lowest % cost variation) among the five pilot plants as a result of the maximization of recycled gypsum incorporation rates. A relatively broad range of impact as well as conflicting trends that vary from positive to negative effects can be clearly observed in almost all the cost elements. These apparent inconsistencies are attributed to the particularities in the process of each pilot plant (i.e. differentiations in the base scenarios) and reflect the different technical adjustments made to each process in the 2nd round of trials. They clearly indicate dependence of the results on the process characteristics.

More specifically, as already noted, even though all the plants that carried out the trials use typical plasterboard production lines, the five processes are not identical. This is considered positive for the study's purposes as it provides a broader range of sample cases. On the other hand, the small number of sample cases (five plants) limits the level of independence of the

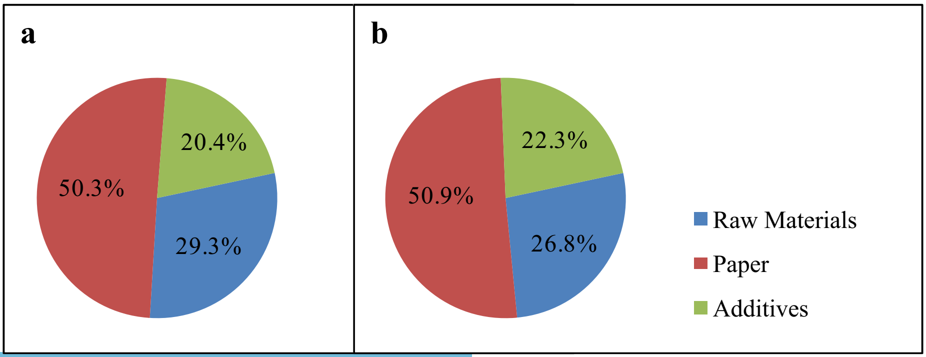

Fig. 5 Materials' cost structure of plasterboard manufacturing for the Base Scenario (**a**) and the High Recycling Scenario (**b**)

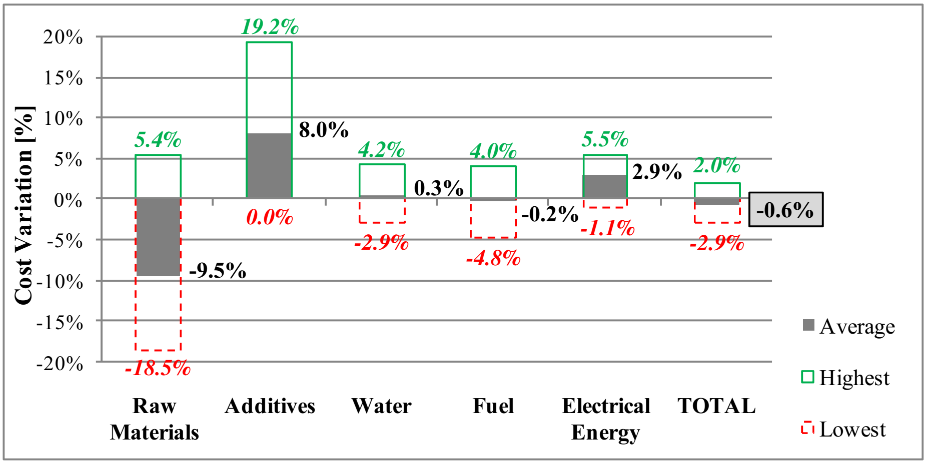

Fig. 6 Average impact and range of impact of recycled gypsum use maximization on variable costs of plasterboard manufacturing

results from process-specific differences. In addition, the recorded parameters depend on the specific set of adjustments made by each manufacturer as a result of the higher recycled gypsum incorporation, according to the particularities of each process; different adjustments could lead to different outcomes. As a consequence, there is "non-homogeneity" in the original collected datasets, which results in these inconsistent impact trends observed on individual parameters among the five separate cases studied. It should be noted that the above observations reflect difficulties encountered during actual production processes. In this sense, the results establish typical deviations that could be expected among different plants.

In this context, the individual levels of impact on total plasterboard cost largely depend on the variable cost structure in each plant; the relative importance of each element (i.e. % share in total cost) relates not only to its respective consumption but also to its unit price. These prices vary considerably among the five plants, due to both process-specific differences (e.g. types of conventional feedstock and/or additives used) and the fact that the plants are located in different countries, the latter most particularly affecting the cost of energy and water. Table 6 is indicative of the appreciable deviations that exist among the cost structures of the five examined plants, which, furthermore, justify the choice of methodology described in Section "Calculations".

The 9.5% average decrease in the cost of raw materials that becomes the determinant factor of the overall impact on the total cost of plasterboard (Fig. 6) is due to the considerably lower cost of recycled gypsum compared to conventional gypsum raw materials; according to the collected data, the market prices of conventional gypsum are currently at least ten times higher than those of the post-consumer recycled material. Despite the broad variation of this variable (from −18.5 to +5.4%), in the 2nd round of trials the raw material cost is in fact reduced in four out of the five plants. In general, a direct decrease in the cost of raw materials per m^2 of plasterboard can be expected to result from the higher usage of the cheaper recycled gypsum in the 2nd trials. This would indeed be the case if the same "batch" of gypsum feedstock were used in both trials. In practice however, usual variations in the properties of feedstock (free moisture and purity) alter the mass balance of the process in terms of the feed/stucco ratio (mass of feedstock needed to produce 1 t of stucco) and the slurry recipe in terms of the amount of stucco

Table 6 Variable cost structure for the two generalized scenarios and respective value ranges in the five pilot plants in the two rounds of trials

Element	Share in total cost			
	Base scenario (1st trials)		High recycling scenario (2nd trials)	
	Value range (plants 1 to 5)	Average value (generalized scenario – Fig. 4a)	Value range (plants 1 to 5)	Average value (generalized scenario – Fig. 4b)
Raw materials	15.4–25.5%	20.5%	13.0–26.3%	18.6%
Paper	24.2–47.6%	35.1%	24.2–46.6%	35.3%
Additives	7.7–23.5%	14.2%	7.5–24.9%	15.5%
Fuel	1.6–29.6%	19.3%	1.5–30.1%	19.4%
Electrical Energy	2.7–16.8%	8.6%	2.7–17.2%	8.9%
Water	0.03–8.3%	2.3%	0.03–8.2%	2.3%

The broad value ranges are due to both process particularities (e.g. differences in recipe), as well as to notable deviations in the unit prices of the elements from plant to plant, partly arising from price differences on geographical level

needed to produce 1 m^2 of board. Given the fact that the 2nd trials were carried out several months later than the 1st trials, different batches of both conventional and recycled gypsum raw materials were used. This resulted in one case in a considerable increase in the feed/stucco ratio compared to the base scenario and caused the respective cost increase recorded in one of the plants.

With regard to the remaining variable cost elements, the fluctuations observed in Fig. 6 relate to the quality characteristics of the recycled material in conjunction with the process adaptations implemented. The introduction or increase of the usage of a certain feedstock component in the process – in this case recycled gypsum – alters a series of properties of the so far standard used feedstock/feedstock mix (e.g. particle size distribution, free moisture content, purity, TOC, presence of impurities etc.), which essentially determine the technical process characteristics that must be adapted in order to overcome or mitigate potential implications, while maintaining the desirable product quality.

A clear trend appears in the cost of additives (Fig. 6). In the 2nd trials, additives consumption is higher in three out of the five plants. This anticipated trend results in an average cost increase of 8%; due to changes caused in the quality characteristics of the feedstock mix, the properties of the stucco slurry most likely have to be restored by adjusting the recipe in terms of the types and amounts of chemical additives used, which are particularly costly. Such adjustments, for instance, may include the use of dispersant and fluidizer additives to restore the viscosity and fluidity of the slurry at lower excess water levels, the use of accelerators to restore the setting time in the boardline etc.

The electrical energy cost presents a mostly consistent augmentative effect, being increased in four of the plants up to 5.5%, whereas the cost of fuel appears significantly affected on individual plant level either positively or negatively within a broad range of −4.8 to 4%, thus resulting in the marginal 0.2% average decrease.

The net average effect on water cost for the generalized scenarios is a slight increase of 0.3%, but varies from −2.9 to 4.2% among the plants, being reduced in three out of the five cases. Possible explanations for the absence of a consistent trend are based on the following facts concerning water consumption issues in relation to process-specific differences:

- Stoichiometric water demand is determined by the hemihydrate content of stucco and, assuming that the same rate of conversion of dihydrate into hemihydrate is achieved on a constant basis during calcination, it is in theory directly proportional to feedstock purity. Recycled gypsum has typically lower purity than conventional feedstock and thus, as its use increases, the purity of feedstock mix and, in turn, stoichiometric water demand is decreased. However, due to usual small fluctuations in the purity of conventional feedstock this effect is not consistently observed in the recorded data; even though the purity of feedstock decreased on average from 91.2 to 90.4% in the generalized scenarios, in two plants the mix's purity is slightly higher in the 2nd trials than the 1st trials due to the use of purer conventional raw materials.
- In practice, fluctuations in the calcination rate of conversion may arise from changes in the particle size distribution of feedstock as a result of the inclusion of recycled gypsum in the mix; longer time is needed for the complete calcination of coarse compared to finer particles. Furthermore, residual paper flakes and fibres from recycled gypsum affect the consistency of feedstock and tend to form agglomerations in the calcining gypsum mass or stick to the walls of indirectly heated calcination vessels and form insulating spots and layers, thus hindering uniform and efficient heat transfer. Potentially higher moisture content of recycled gypsum may also influence the calcination efficiency of the mix when single unit calcination equipment is employed. All such effects can alter the phase composition of stucco (hemihydrate, unreacted dihydrate, potential formation of anhydrite). The occurrence of undesirable phases that negatively affect the intended properties of stucco can be minimized by thorough control of the calcination conditions (temperature, pressure, heating and stirring methods and rates, etc.), but, in any case, the net effect on stoichiometric water demand can be different for each plant, depending on the standard feedstock and process characteristics.
- The optimum water/stucco ratio depends before all on raw material nature and particle size. Therefore, changes in the particle size distribution of stucco also affect the excess water demand in the slurry mixer. This impact can accordingly differ among the studied plants depending on the type of standard feedstock used (i.e. natural and/or FGD gypsum) and the implemented process modifications (e.g. by adjusting certain additives such as liquefiers).
- The increased TOC (paper and fibres) in feedstock caused by the high incorporation of recycled gypsum negatively affects the fluidity of the slurry and increases the excess water demand. This impact can be mitigated by the use of appropriate additives, but the net individual effect can be, again, different in each plant.

Impact on variable costs per process stage

The impacts identified in the previous section can be further analyzed with regard to the two distinct process steps; Stucco Production and Plasterboard Production (see Table 4). As shown in Fig. 7, the Plasterboard Production stage accounts for the higher share of plasterboard manufacturing cost, around 70% for both generalized scenarios. The observed cost shift of 1.5% from the Stucco Production to the Plasterboard Production stage essentially indicates a decrease in the cost of Stucco Production, at the expense, however, of Plasterboard Production cost. A clearer insight is provided in the related Figs. 8 and 9 for each production stage.

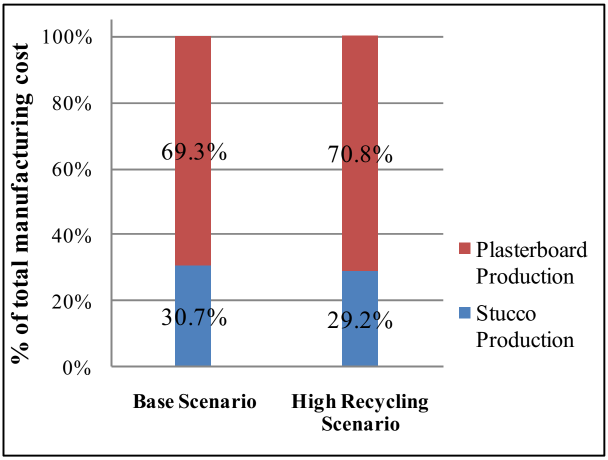

Fig. 7 Cost structure of plasterboard manufacturing per process stage

The variable costs of the Stucco Production stage consist of raw materials, fuel and electricity. Figure 8 shows that the average cost of Stucco Production is reduced by 5.5% in the High Recycling Scenario compared to the Base scenario. This rather notable decrease is again due to the 9.5% drop of raw materials' cost which overweighs the increases of the energy cost parameters and determines the overall impact.

The reasons for the apparent discrepancies in the range of impact in Fig. 8 have already been discussed in the previous section. As shown in Fig. 8 the impact on total Stucco Production cost varies between −9.9 and 6.1% among the five pilot plants. However, the trend is mostly decreasing; the total cost is reduced in four out of the five plants. The cost of fuel shows an average increase of 1.1%, while electricity cost is increased rather significantly. The markedly broad ranges of impact on both energy cost elements arise from the different effects caused by the higher inclusion of recycled gypsum on the quality parameters of the feedstock mix in each plant, particularly moisture, purity and particle size, depending on the respective attributes of the

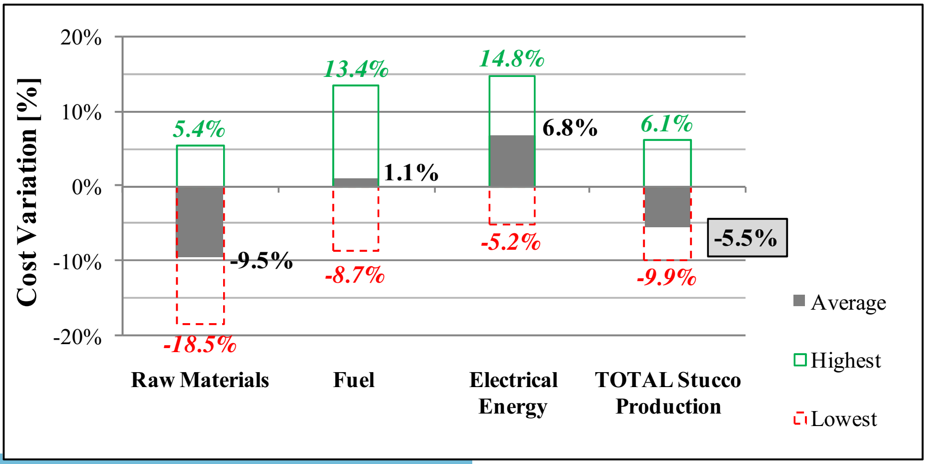

Fig. 8 Stucco Production stage – Impact and range of impact of recycled gypsum use maximization on variable costs

recycled material used in each case in relation to those of conventional raw materials. The thermal energy demand of the feedstock pre-drying and calcination operations, as well as the process mass balance in terms of the feed/stucco ratio and the handled materials' bulk densities are both affected by these quality characteristics, and these changes combined with the accordingly implemented adjustment options (e.g. process parameter control, speed of machinery etc.) eventually form the impact on fuel and electricity costs in the five plants for this production stage. More information regarding the effects of the high-level usage of recycled gypsum on the energy consumption of the process can be found elsewhere [12].

The corresponding impact on the variable costs of the Plasterboard Production stage is presented in Fig. 9. The costs of this stage consist of paper, which is excluded from the analysis as already explained, chemical additives, fuel, electrical energy and water. The average total cost appears increased by 1.6% in the High Recycling Scenario compared to the Base scenario. The increase in this case mainly arises from the 8% raise of the additives' cost, and to a lesser extent from the 1.3% increase in the cost of electricity. The impact on total Plasterboard Production cost shows a consistent increasing trend among the plants studied, varying from 0.1 to 4.2%. The effects on additives and water have already been discussed. The broad variations of fuel cost on individual plant level are explained by what has already been discussed regarding excess water, which practically determines the fuel demand for this stage, as well as by any changes that may have occurred in the drying behavior of plasterboard arising from the effects on feedstock characteristics and/or any potential effects on stucco properties. The individual impacts on electrical energy consumption are relatively small and relate to changes and adjustments in the load and speed of the boardline, resulting from possible effects on the mass balance and on the setting time of stucco respectively.

Sensitivity analysis

Uncertainty margins

The quantification and recording of certain process parameters has in fact proven difficult in practice given the finite time interval of testing as opposed to

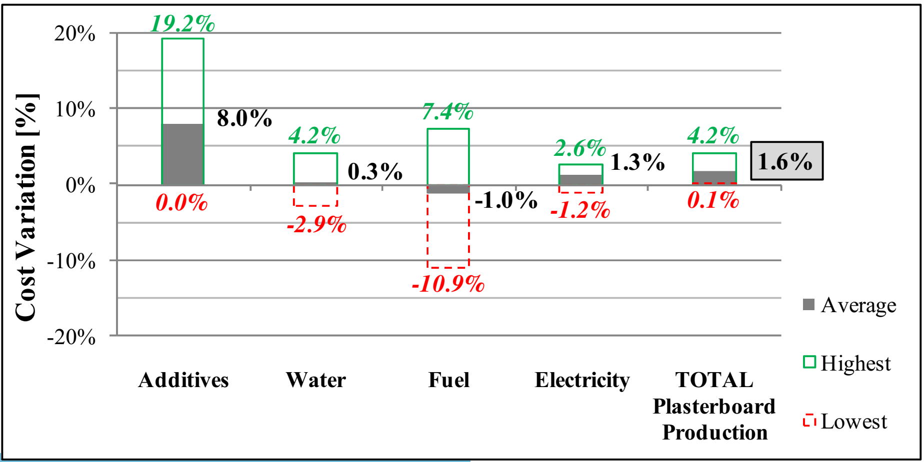

Fig. 9 Plasterboard Production stage – Impact and range of impact of recycled gypsum use maximization on variable costs

manufacturing on a daily and continuous basis. This may limit the accuracy of the input data used for the techno-economic assessment. In order to estimate the corresponding uncertainty margin of the results, a sensitivity analysis has been performed by varying the key input parameters that may affect the uncertainty. These are specifically all the energy and certain material consumption values (additives, water and paper) provided by the manufacturers. Raw material consumptions refer to the specific recycled gypsum incorporation rates achieved and for this reason are not included in the sensitivity analysis.

The variation of the plasterboard manufacturing costs (Fig. 6) is found to be highly sensitive to the accuracy of the input data; by simultaneously varying all the inputs within a range of ±5%, the average impact on total variable plasterboard manufacturing cost varies from −4.6 to +3.8%. Therefore, within the boundaries of uncertainty in this assessment, the calculated average 0.6% decrease of total variable plasterboard cost (see Fig. 6) is too small to conclude a categorical cost benefit in increasing the content of recycled gypsum up to ca. 30% in Type A plasterboard production. In reality, potential savings or losses will probably lie between the estimated uncertainty thresholds.

Impact assessment in relation to price increases of variable cost elements

Aside from the uncertainties, recycled gypsum incorporation in the plasterboard manufacturing process at high levels appears economically favorable in absolute terms compared to the generalized Base Scenario. In the framework of a threshold analysis, the maximum price increases of the individual variable cost elements at which the total plasterboard cost per m^2 of plasterboard at the High Recycling Scenario equals the respective cost of the Base Scenario can be defined as Breakeven Points (BEPs). The calculated BEPs given in Table 7 are essentially the maximum market price increases in materials and energy that the manufacturers can "afford" to fully redeem the benefit gained if the usage of recycled gypsum at the maximum feasible levels becomes standard practice.

A single factor sensitivity analysis has also been performed to investigate the extent to which the net impact on total plasterboard cost is influenced by potential variations (up to ±30%) in the market prices of the main elements affected by the use of recycled gypsum, i.e. conventional raw materials, additives, water, fuel and electricity. It is noted that average unit price values, based on the actual input data from each plant, were used in the sensitivity analysis as well as in the calculation of BEPs.

It is found that the impact on the average total variable plasterboard manufacturing cost as a result of the maximized use of recycled gypsum shows little influence to electricity price variations; 30% rise in prices causes the savings in plasterboard cost to shrink from −0.6 to

Table 7 Breakeven points (BEPs) of individual variable cost elements

Cost element	BEP
Conventional raw materials	3.3%
Paper	1.7%
Additives	3.8%
Water	27%
Fuel	3.0%
Electrical energy	6.7%

−0.5%. This is due to a respective effect on Stucco Production cost, as the cost of the Plasterboard Production stage remains practically unaffected.

With lower than 5% influence from price variations of up to 30%, the impact on total plasterboard cost is also evaluated as non-sensitive to fuel prices. Expectedly, given the low level of effect of recycled gypsum use on water (Fig. 6) and the low share of water in the cost structure (Fig. 4), the impact also shows no sensitivity to water price variations.

The impact is found to be most sensitive to the prices of conventional raw materials and additives, considering the significant shares of these two elements in the cost structure (see Fig. 4) and given the fact that they result to be the most affected by the use of recycled gypsum (Fig. 6). The related results are presented in Fig. 10, which illustrates the combined influence of these two main sensitivity factors on total plasterboard cost.

More specifically, increases in the prices of conventional raw materials raise the positive impact of recycled gypsum incorporation on final plasterboard cost. A price increase of 30% doubles the achieved benefit, from currently −0.6% to ca. −1.2%. On the contrary, the use of recycled gypsum is not favored by additives' price increases, which cause greater negative effect on the cost of the Plasterboard Production Stage and thus reduce the overall cost benefit achieved by the high incorporation of recycled gypsum; for example, 10% rise of prices lowers the benefit from −0.6 to −0.5% (Fig. 10). Still, in order for the impact on total plasterboard cost to become negative, manufacturers can theoretically "afford" increases of up to ~55% in the prices of additives (a highly unlikely development), according to the calculations for the generalized scenarios.

Figure 10 essentially shows that approximately equal or even greater beneficial impact on plasterboard cost can be achieved in a series of cases, where potential increases in the prices of additives are amortized if rises occur in conventional gypsum prices that favor the high incorporation of recycled gypsum. For example, price increases of 5% in additives and of 20% in conventional feedstock result in higher savings of −0.9% compared to the current −0.6% average benefit. As opposed to that, highly increased additives prices at (close to) current conventional

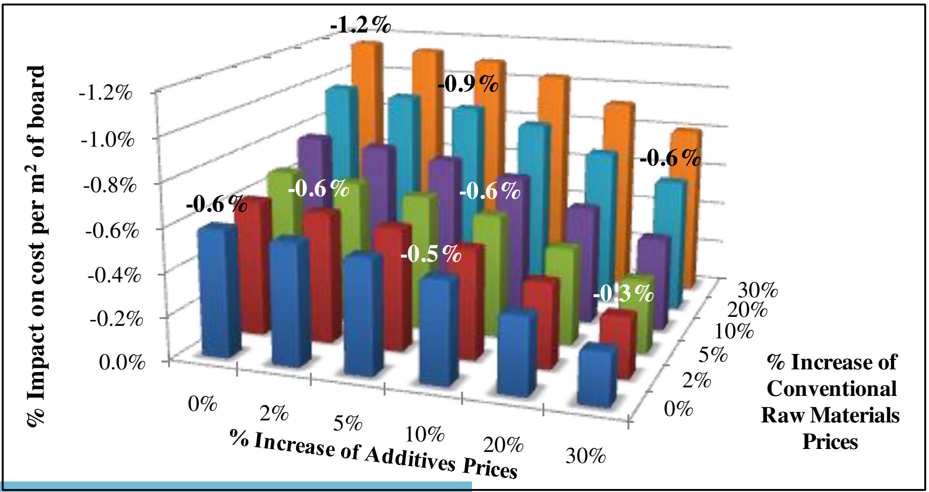

Fig. 10 Impact of price increases of conventional gypsum and additives on the cost of plasterboard with high recycled gypsum content (0% increase represents impact at current price levels)

feedstock price rates tend to shrink the cost savings gained, e.g. 30% increase in additives' prices and 2% in conventional raw materials leads to lower savings of −0.3%.

Summary of techno-economic impacts

The assessment refers to the quality characteristics of the recycled material used in the studied trials. In this regard, the specifications set for recycled gypsum and the consistency of its characteristics are considered critical in achieving a minimum or no impact on the process with minimum adaptations. Thus, given the lower market price of recycled gypsum compared to conventional gypsums, stronger economic benefits can arise when recycled material quality relies consistently within established specifications.

Furthermore, the results of the study are based on the specific market prices of each country as provided in the datasets. As explained in "Calculations" section, and based on the chosen methodology, the average % impact on the individual variable costs given in Fig. 6 correspond to the impacts on the respective consumptions. Hence, accounting for process particularities, a rough expected effect on total plasterboard cost can be deduced if these average % impacts are multiplied by the respective actual costs per m^2 of board of a given plant. For example, assuming a plant with current total cost per m^2 of plasterboard x_{PB}, consisting of the costs x_{RM}, x_A, x_W, x_F, x_E and x_P for raw materials, additives, water, fuel, electricity and paper per m^2 respectively according to Eq. (1), the indicatively expected cost x'_{PB} after the incorporation of recycled gypsum can be calculated by Eq. (2):

$$x_{PB} = x_{RM} + x_A + x_W + x_F + x_E + x_P \tag{1}$$

$$x'_{PB} = 0.905 \cdot x_{RM} + 1.080 \cdot x_A + 1.003 \cdot x_W + 0.998 \cdot x_F + 1.029 \cdot x_E + x_P \tag{2}$$

The impact on total cost is the percentage difference of x'_{PB} compared to x_{PB}.

By varying the coefficients of (2) within the respective ranges of impact shown in Fig. 6, the highest and lowest values of x'_{PB} can be calculated, offering a representative value range for the net impact on total plasterboard cost. This obtained range is in turn indicative of the different effects of various sets of process adjustments that can be considered, serving as a starting point for potential planning of test productions and optimization. The empirical coefficients and the correlation of Eq. 2 are derived from the incorporation of recycled gypsum up to around 30% by weight in feedstock in the five sample plants. Given that the five plants are among the most representative in Europe (in terms of process variations, capacity and raw material mix), Eq. (2) can serve as a basis in any typical plasterboard manufacturing plant for an indicative assessment of the cost impacts caused by incorporation of recycled gypsum in feedstock up to the maximum examined.

Overall, the analysis of the results has shown that the impacts of incorporating recycled gypsum in plasterboard manufacturing may be multiple and in some cases reinforced by correlated and/or conflicting effects. Many adjustment options that readily address the impact on individual manufacturing parameters may negatively affect other process variables and may therefore need reconsideration. In any case, the present study shows that the use of recycled gypsum offers potential for cost savings, as evidenced by the range of impact results at individual plant level, as well as by the sensitivity analysis. However, the differentiations and individualized practices followed at each plant do not allow the development of a generalized methodology, including a standardized set of process adjustments, for the optimum/highest inclusion rate of recycled gypsum in the process. Hence, after investigation and assessment of the available solutions, the corrective actions taken at the first stage of implementation must be reassessed and followed by optimization and fine-tuning of the process to arrive at the best possible outcome, i.e. minimum impact on product quality and cost.

Table 8 summarizes the parameters that may be potentially affected by the introduction or increase of recycled gypsum usage in the process, the resulting impacts as identified in this study and the respective options for adjustments and corrective measures, as well as their effects on costs. It also includes a few permanent process modifications that involve capital investment from the manufacturers' part. Such modifications were not implemented as part of the studied production trials. However, such investments may become necessary, as long as high-level usage of recycled gypsum turns into standard practice. From the cost point of view, process modification investments may become more attractive in the near future, depending on raw material prices and national legislations, e.g. gate fees for landfilling, landfill tax [26].

Finally, with regard to impurities, even though according to their characterization, the recycled gypsum samples from the trials were mostly found to conform to the required specifications for technical parameters and trace elements, the content values of certain impurities –expectedly– appear elevated for the recycled material compared to conventional gypsum. However, the impact of recycled gypsum usage on product quality and production rate in relation to the presence of such impurities (e.g. water soluble salts) could not be assessed based on the present study's results; no clear trend could be deduced to link the generation of off-spec boards with comparatively higher contents of specific impurities in feedstock. This could be partly due to the limited number of available datasets and the short duration of the trials. In any case, an indicative reference of such potential impacts is included in Table 8.

Conclusions

The current work "isolates" and clearly identifies the effects of high-level recycled gypsum incorporation on the variable costs of plasterboard manufacturing within a strictly defined scope that includes all process stages affected by its usage. The study provides useful insight regarding the practical issues of recycled gypsum incorporation and the identification of the resulting impacts on the process. The compilation of specific and up-to-date information from real production data adds to the importance of the findings and the proposed methodology can serve as a guideline for techno-economic assessment of industrial production lines where the input datasets originate from different plants and can be characterized as "non-homogeneous" due to case-specific differences. Conclusions are summarized below:

- The introduction or increase of recycled gypsum up to 30% by weight in feedstock in Type A plasterboard manufacturing is proven feasible, even under the adverse conditions of non-permanent process adjustments.
- Individual process costs are affected, but the calculated net average impact on the total variable manufacturing cost is practically negligible; the key impact observed is a limited

Table 8 Summary of potential techno-economic impacts and adjustment options

Affected process parameter	Potential impact(s) on the process	Potential process adjustment(s)	Affected plasterboard cost parameter(s) (+, − or ±)[a]
Feedstock mix	Partly substitution of conventional feedstock by recycled gypsum	N/A	Raw materials (−)
	Insufficient (indoor) storage spaces for recycled gypsum	Designation of new spaces in existing storage facilities including separate spaces for "quarantined" recycled gypsum stock intended for return / Investment in new storage spaces **(P)**[b]	N/A
	Overload/ insufficiency of recycled material feeding systems to meet increased incorporation rates	Re-design of raw material feeding systems / Up-scale of recycled gypsum feeding systems **(P)**	Electrical Energy (+)
	The recycled material may have different pre-processing requirements than the conventional feedstock used (e.g. no primary crushing needed as opposed to natural gypsum)	Introduction of recycled gypsum at the appropriate process point	Electrical Energy (−)
Feedstock particle size distribution	Effect on calcination efficiency (changes in phase composition of stucco, occurrence of undesirable phases)	• Additional sieving and/or grinding depending on the type(s) of conventional feedstock used **(P)**	Electrical Energy (+)
		• Calcination conditions (temperature, pressure, heating / stirring rate etc.)	Fuel (±)
	• Effect on calcination thermal energy demand	Calcination conditions	Fuel (±)
	• Effect on stoichiometric water demand of slurry	Recipe (water)	Water (±)
	• Effect on stucco quality/ intended properties	Recipe (stucco dosage and additives)	Raw materials (±) Additives (+)
	Effect on the fluidity of the stucco slurry	Recipe (additives and water)	Additives (+) Water (±)
	• Effect on excess water demand	Recipe (water)	Water (±)
	• Effect on thermal energy demand for drying of plasterboard	Drying conditions	Fuel (±)
Feedstock moisture content	Effect on thermal energy demand for pre-drying of feedstock	• Mixing of wet with "drier" recycled gypsum batches to reduce the feed's moisture	Fuel (±)
		• Pre-drying conditions	Fuel (±)
	Effect on calcination efficiency in single-unit calcination equipment	Calcination conditions	Fuel (±)
	Effect on process mass balance (feed/stucco ratio, calcination throughput)	Load and speed of feeding systems to maintain production rate	Raw materials (±) Electrical Energy (±)

Table 8 (continued)

Affected process parameter	Potential impact(s) on the process	Potential process adjustment(s)	Affected plasterboard cost parameter(s) (+, − or ±)[a]
Feedstock purity	Effect on calcination thermal energy demand	Calcination conditions	Fuel (±)
	Effect on stoichiometric water demand of slurry	Recipe (water)	Water (±)
	Effect on process mass balance (feed/stucco ratio, bulk densities of materials, calcination throughput, density of plasterboard)	Load and speed of equipment to maintain production rate	Raw materials (±) Electrical Energy (±)
	Effect on stucco quality (bulk density, setting)	Recipe (stucco dosage and additives)	Raw materials (±) Additives (+)
Feedstock TOC content (and size of residual paper flakes)	Equipment blockages (sieves, mixer) • Effect on production rate due to interruptions and delays	N/A	Total cost (+)
	Effect on calcination efficiency and thermal energy demand (hindering of uniform heat transfer in the calciner)	Calcination conditions	Fuel (±)
	Increase of excess water demand	Recipe (additives and water)	Additives (+) Water (+)
	• Increase of thermal energy demand for drying of plasterboard	Drying conditions	Fuel (+)
Setting time	Effect on the setting behavior/time of the boards' plaster core	Recipe (Additives) Boardline speed	Additives (+) Electrical Energy (±)
Feedstock composition (presence of impurities)	Effects on product quality (e.g. core-paper bond, blisters in core etc.)[c]	Recipe (Additives)	Additives (+)
	• Increase of generated off-spec boards, effect on production rate		Total cost (+)

[a] Increase, decrease or variable respectively

[b] (P) indicates permanent measures not implemented during the production trials

[c] Included only as indicative potential impact, not as result of the present study

0.6% total cost reduction arising from a considerable decrease of raw material cost that fully compensates for the cost increases caused to other process parameters.

- The higher-level usage of recycled gypsum necessitates a series of process adjustments which level the potential cost benefits, predominantly due to the requirement of higher amounts of relatively costly chemical additives.
- The impact on total manufacturing cost corresponds to an average 5.5% decrease in the cost of Stucco Production stage which overweighs the respective 1.6% increase in the Plasterboard Production stage.
- Based on the sensitivity analysis, the calculated impact on total cost is too small to conclude measurable benefits or losses from the up to 30% inclusion of recycled gypsum in Type A plasterboard production, given the estimated relatively wide boundaries of uncertainty of the assessment. However, the higher-level usage of recycled gypsum is concluded as favorable to market price increases of conventional raw materials, although the benefits gained are negatively influenced by potential increases in the prices of additives. The impact on total plasterboard cost is evaluated as little sensitive or insensitive to the prices of electricity, fuel and water.
- The results indicate high dependence on process-specific characteristics. However, the narrow range of effect on total plasterboard cost among the studied plants shows clearly that manufacturers managed to minimize the impact by appropriately adapting the process, regardless of the existing differentiations.
- The study summarizes the parameters that may be potentially affected by the introduction or increase of recycled gypsum usage in the process, the corresponding impacts and effects on costs and the respective options for adjustments and corrective measures. These qualitative results are considered global, as demonstrated by full-scale industrial production trials in five of the most representative plants in Europe, covering a wide range of process variations, capacity and raw material mix.
- The empirical correlation proposed in the study can serve as a basis for a representative cost impact assessment of high-percentage recycled gypsum incorporation in typical plasterboard plants.

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