GTOG: From production to recycling: a circular economy for the European gypsum Industry with the demolition and recycling Industry

REPORT ON PRODUCTION PROCESS PARAMETERS

Start date of the project: 2013/01/01

Duration: 36 months

LIFE PROGRAMME: LIFE11 ENV/BE/001039

Identifier:	**DB4: Report on Production Process Parameters**
Number of the associated action:	**B3**
Date:	**October 2015**
Class:	**Deliverable**
Responsible partner:	**Knauf Gips (KNAUFKG)**
Distribution:	**PU (Public)**
Title:	**Report on Production Process Parameters**

Contact Information

Lead Contact	Eurogypsum – Christine Marlet
Phone Number	+32 2 227 11 30
Email	info@eurogypsum.org

Document Contact	Prof. Maria Founti, National Technical University of Athens (NTUA)
Deliverable	**DB4: Report on Production Process Parameters**
Phone Number	+30 210 7723605
Email	mfou@central.ntua.gr
Participants	Knauf Gips (KNAUFKG), Siniat FR (L1), Siniat Ltd UK (L2), Saint-Gobain Placoplatre (SG1), Saint-Gobain Construction Products Belgium NV – Gyproc (SG2), National Technical University of Athens (NTUA), Fundacion General Universidad Politecnica de Madrid (LOEMCO)

GTOG Project Management Bureau

Name	**Title**	**Phone**	**Email**
Christine Marlet	Project Director	+32 2 227 11 30	info@eurogypsum.org
Luigi Della Sala	Project Manager	+32 2 227 11 62	project@eurogypsum.org
Thierry Pichon	ERMC Chair/President of the GtoG SC		Thierry.Pichon@siniat.com

Document History

Version	Date	Author(s)
00	15.12.2014	NTUA (N. Papailiopoulou, E. Grigoropoulou, M. Founti)
Comments on version 00	12.01.2015	SG2 (Tom Rommens)
	12.01.2015	KNAUFKG (Jörg Demmich)
	12.01.2015	SG1 (Philippe Marivin)
	12.01.2015	Siniat FR (Martin Bonaimé)
	12.01.2015	Siniat UK (Richard Hildersley)
	12.01.2015	LOEMCO (Daniel del Barrio)
01	20.02.2015	NTUA (N. Papailiopoulou, E. Grigoropoulou, M. Founti)
02	03.06.2015	NTUA (N. Papailiopoulou, E. Grigoropoulou, M. Founti)
Comments on version 02	10.06.2015	Siniat FR (Martin Bonaimé)
	11.06.2015	KNAUFKG (Anna Lang)
	11.06.2015	Siniat UK (Richard Hildersley)
	11.06.2015	LOEMCO (Daniel del Barrio)
	15.06.2015	SG1 (Philippe Marivin)
	15.06.2015	SG2 (Tom Rommens)
03	22.06.2015	NTUA (N. Papailiopoulou, E. Grigoropoulou, M. Founti)
Comments on version 03	29.06.2015	LOEMCO (Daniel del Barrio)
	29.06.2015	Peer Review by UPM Team
04	01.07.2015	NTUA (N. Papailiopoulou, E. Grigoropoulou, M. Founti)
Comments on version 04	22.07.2015	GipsRecycling (Henrik Lund-Nielsen) –comments on steering committee presentation of NTUA
	22.07.2015	Siniat FR (Martin Bonaimé)
	22.07.2015	KNAUFKG (Anna Lang)
	22.07.2015	NWGypsum (Maarten Hendriks)
	22.07.2015	Recycling Assistance BVBA (Johan D'Hooghe)

	22.07.2015	Siniat UK (Richard Hildersley)
	22.07.2015	UPM (Justo Garcia Navarro)
	23.07.2015	SG2 (Tom Rommens)
	27.07.2015	REC (Jean Yves Burgy)
05	13.09.2015	NTUA (N. Papailiopoulou, E. Grigoropoulou, M. Founti)
Comments on version 04	14.09.2015	GRI (Henrik Lund-Nielsen)
06	28.09.2015	NTUA (N. Papailiopoulou, E. Grigoropoulou, M. Founti)
07	12.10.2015	NTUA (N. Papailiopoulou, E. Grigoropoulou, M. Founti) Incorporation of final comments of GtoG partners
Comments on version 07	12.10.2015	SG1, SG, SiniatFR, SiniatUK, KNAUFKG– removal of cost data
08	14.10.2012	NTUA (N. Papailiopoulou, E. Grigoropoulou, M. Founti)

Table of Contents

GYPSUM TO GYPSUM

Table Index

Figure Index

Executive Summary

Deliverable DB4 reports the outcome of the joint efforts of the five manufacturing plants participating in the GtoG project to address the main scope of Action B3, namely increase the re-incorporation percentage of recycled gypsum in Type A plasterboard manufacturing up to 30% and identify related bottlenecks. This joint effort highlights the full engagement of plasterboard manufacturers to develop recycling practices that will permit higher re-incorporation percentages.

Gypsum products are indefinitely and 100% recyclable, due to the gypsum chemistry, and they can always keep their natural properties during use. It is current practice in most plasterboard manufacturing plants to re-incorporate (recycle) own production wastes in the gypsum board production. This results in up to ~5% inclusion of re-processed secondary gypsum as raw material in the board. Moreover, some plants have recently started to introduce the usage of post-consumer recycled gypsum (i.e. secondary gypsum derived from construction and demolition/deconstruction gypsum-based waste) raising the above percentage to ~10-15%.

One of the challenges addressed in the GtoG project is to deal with this post-consumer recycled gypsum, a more complex raw material with variable characteristics, by increasing the percentage that can be re-incorporated into standard plasterboard production lines aiming to achieve a target of 30% recycled gypsum in plasterboards. The technical feasibility of this target is investigated in the framework of Action B3 – "Towards Sustainable Lightweight Systems" of GtoG and the respective impact on the plasterboard manufacturing process is techno-economically assessed. The results are presented in this report.

Data Collection

The study is based on data obtained from full scale industrial "standard" plasterboard (Type A) production trials carried out in two rounds from January 2014 until March 2015 in five plasterboard manufacturing plants located in France (2 plants), the UK, Germany and Belgium. The so-called "1st round of trials" refers to a series of runs *of the standard production* in each plant, which includes all the different raw material streams as well as the standard percentage of recycled gypsum (i.e. the percentage of recycled material that each plant re-incorporates in their everyday business), and serves as a Base Scenario for the impact assessment. The "2nd round of trials" involves (repeated) test productions with gradually increasing amounts of recycled gypsum, above the current percentage (if any) and up to the set target of 30% or up to a technically feasible maximum, defined either by product quality and/or process effectiveness according to process-specific technical features.

Data collection includes three sources:

- the receipt of samples of raw materials (conventional and recycled) and products from the five plants for property analysis
- the systematic recording of the key techno-economic parameters of the plasterboard manufacturing process (material and energy consumptions, mass flow rates, process conditions data, cost data) using templates adjusted to each plant's individual process characteristics and regular practices

- ground observations made during visits of the NTUA team to the five plants after the completion of the 1st round of trials (June 2014) and observations of the manufacturers summarized in questionnaires after the 2nd round of trials regarding the impact on the process and the adjustments that were required.

Plasterboard Manufacturing Process

Plasterboards are manufactured in a two-step process. The first step's generic stages include pre-processing of the gypsum feedstock (size reduction and pre-drying depending on feedstock type and properties), followed by the thermal process of calcination. The intermediate product is stucco, a partly dehydrated form of gypsum, which is then mixed with water and additives to form the plaster slurry. In the second step, the slurry is fed to the board line where it is encased between two layers of special strong paper and gradually sets while it is conveyed along the line at an appropriate speed. When set, the continuous length of plasterboard is cut to individual uniformly sized boards, which are transported through a large multi-zone drier to remove the excess free water and exit as the finished product.

The feedstock mix for the production of stucco may consist of one or more types of gypsum from conventional sources (natural and/or synthetic – FGD). Feedstock can also contain a percentage of recycled gypsum derived from production waste and/or post-consumer gypsum-based waste from construction and demolition/deconstruction jobsites. In any case, each individual gypsum type, as well as its source, must be assessed regarding its particular suitability for plasterboard manufacturing, which may vary depending on purity or other technical and toxicological parameters of the material.

In this respect, the selected plants produce plasterboards using typical production line configurations, which include the above described typical production steps. However, the processes in the five manufacturing plants are not identical. Differences exist in the feedstock/feedstock mix used and consequently in the raw material pre-processing stages (grinding, sieving, pre-drying etc.) as well as in calcination, recipes and the industrial equipment employed.

Outcome of the Trials – Key Manufacturing Parameters of Plasterboard Manufacturing Process

The origin, type and properties of the raw materials are major determinant factors of the technical characteristics of a production process, which is adapted accordingly in order to efficiently achieve the desirable product quality. The introduction or increase of recycled gypsum in the process alters the composition of the feedstock/feedstock mix and may alter its quality related characteristics and properties, such as particle size, free moisture, purity etc, in case that these are different from the respective ones of the feedstock used before. This, in turn, has an effect on technical production issues that may call for process modifications (e.g. new silos, new dimensions – speed of conveyor belts, setting times, recipe modifications) in order to minimize and/or eliminate negative implications on product quality, as well as on production costs.

In this context, the key parameters of the plasterboard manufacturing process that are affected by the use of recycled gypsum as identified in this study can be grouped into two main categories, based on the scope of respective impact; feedstock quality and technical process features. Essentially these are closely interlinked and co-dependent. The first group comprises particle size, free moisture, purity, residual paper and fibre content of recycled gypsum (TOC), water soluble salts, silicon content of recycled gypsum, other impurities in recycled gypsum and feedstock pH. The technical process related parameters are storage, raw material feeding, process conditions (mainly temperatures), slurry dosage, water demand, setting time and variable manufacturing costs.

The 1st round of trials refers to the "business as usual" of every plant. The specific 1st trial performed in the frame of GtoG served to provide reference quantitative data for comparison with the results of the 2nd trial. The quantitative results are supported by ground observations and experiences gathered from the normal everyday practices of each plant. Based on the latter, it is stated that potential process effects may be tolerated and/or easily overcome at relatively low re-incorporation levels of recycled gypsum (5-18%). This is currently achieved by addressing potential quality fluctuations of the recycled material (e.g. associated with provision of recycled material by different suppliers) on a case-to-case basis. This "non-standardized" approach restricts the continuous and systematic increase of the percentages used in the daily production practices.

Based on the outcome of the 2nd round of production trials, it is reported that higher level re-incorporation of recycled gypsum into plasterboard manufacturing has proved feasible in practice; the re-incorporation of recycled gypsum has been increased considerably, from originally 5-18% in the 1st round of trials to 20-30% in the 2nd without any permanent investment in equipment and infrastructure from the manufacturers' part.

The production trials of the GtoG project proved the feasibility of the re-incorporation increase of recycled gypsum mix for the five examined plants from an average of ~11% in the standard practices to an average of ~25%. However, the GtoG target of 30% was not fully reached by each individual plant due to three main reasons: a) non-availability of necessary amounts of recycled material that would have allowed repeated trials (only one trial was foreseen in the time frame of the project); b) limitations in the capacity of the production process equipment; c) some issues related to the characteristics of received recycled gypsum that necessitated recipe adjustments.

Problems and difficulties encountered during the 2nd round of trials were overcome by appropriate, non-permanent, production process adjustments that took into consideration the duration of the trials, the achieved % inclusion rate and the characteristics of the recycled material used in each case. Feeding system capacity limitations and recycled gypsum quality related issues, mainly residual paper content and to a lesser extent free moisture and purity, are reported by the manufacturers as the main factors that limited the further increase of the re-incorporation rate during the trials.

Property Analyses of Raw Materials and Products

With very few exceptions, the vast majority of delivered recycled gypsum samples complied with the respective proposed specification limits (see DB2.2). The analyses of conventional gypsum samples served as reference to assess recycled gypsum physicochemical characteristics.

Considering the property analyses of the product samples, the reincorporation of recycled gypsum up to 30% does not noticeably affect the basic performance characteristics of Type A plasterboards; all samples from the 2nd trials were found to conform to the EN-520 Standard.

Techno-economic Assessment of Recycled Gypsum Incorporation into the Plasterboard Manufacturing Process

Scope and Functional Unit

The study specifically focuses on the production process of "standard" plasterboard (Type A) and its scope is restricted within the manufacturing plants' boundaries. The functional unit is 1 m^2 of "standard" plasterboard (Type A) with 12.5 mm thickness, which is the type of plasterboard produced in the lines where the production trials were carried out.

The system boundaries are defined to include all processes, starting from the entrance to the manufacturing plant until the production of the finished plasterboard. Further upstream and downstream operations, such as raw material and recycled gypsum production, product packaging, product distribution etc., as well as labour costs, do not fall into the scope of study, since their respective energy demands and costs remain unaffected by the introduction of recycled gypsum in the process.

Figure 1 is a schematic of the defined system boundaries and intends to cover all possible practices followed in each plant concerning recycled gypsum; standard common practices for all 5 plants are shown in solid lines, whereas the practices that differ from plant to plant are shown in dashed lines. Transportation of conventional raw materials is included in the system boundaries only when it is carried out by the manufacturer with its own means. Recycled gypsum is delivered to the plants by the recycler companies.

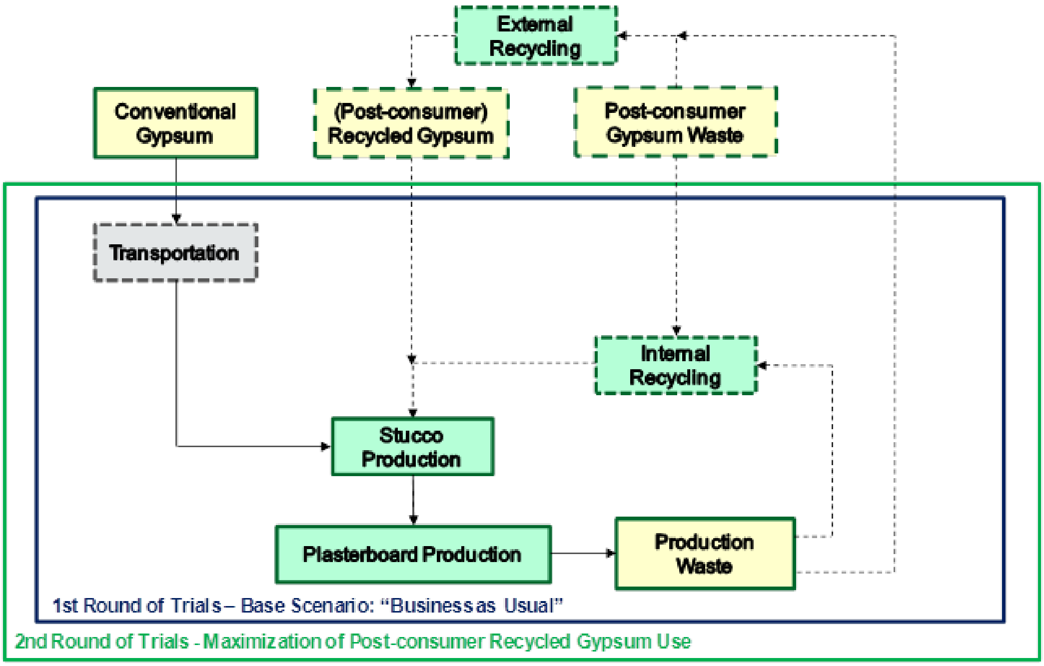

Figure 1 Generalized system boundaries of techno-economic assessment

The term "post-consumer gypsum waste" refers to the gypsum-based waste arising from construction and demolition/deconstruction activities. Post-consumer recycled gypsum is the gypsum powder (ready to be re-used as raw material) derived from the recycling of these wastes.

Study Limitations
The study was conducted using actual production and cost data from the 1st and 2nd round of trials, delivered by each manufacturer to NTUA (in the frame of bilateral confidentiality agreements with each manufacturer). However, the manufacturing and cost parameters of each plant are subject to commercial confidentiality and the presentation of the assessment results is necessarily limited in reporting only percentage variations. Average as well as percentage values are reported for energy consumption.

Two generalized scenarios are developed based on the corresponding data from all five plants; the "Base Scenario - Business as Usual" (1st round of trials) and the "Maximized % Use of Recycled Gypsum Scenario" (2nd round of trials). The reported values of average impact refer to the generalized scenarios, while the highest and lowest values show the respective impact range among the individual results of the plants.

Other limitations of the present study include the small number of sample cases, the "non-homogeneity" of the collected datasets due to existing differences in both the process characteristics and the necessary modifications/ adjustments at each plant, and data quality/accuracy issues; these are considered to increase the uncertainty margin of the generalized average results.

Methodology
Plasterboard manufacturing costs and energy consumption are calculated for each of the five processes based on the data collected during the 1st and the 2nd round of production trials, using the ASPEN Plus 2006 Simulation Software. The impact of the increase of the % re-incorporation of recycled gypsum is assessed for each plant by comparing the two sets of results (results from the 1st and the 2nd round of production trials). The costs for the generalized scenarios are calculated by multiplying the average consumption of each individual cost element (e.g. conventional raw materials, additives, fuel etc.) by the respective average price of the element.

Results
The GtoG 30% re-incorporation target was reached in 2 out of the 5 plants. Main process adjustments implemented during the 2nd round of trials include:

- Changes in the speed of equipment (feeding conveyors, boardline etc.)
- Recipe adjustments concerning the chemical additives used in the stucco slurry

The average impact on costs for the five plants is shown in Figure 2. Overall, the re-incorporation of recycled gypsum up to the feasible maximum for each plant decreases raw material costs. This decrease fully compensates cost increases noted in other process parameters and results in an average 0,6% reduction of the total variable cost per m^2 of plasterboard compared to the Base Scenario. For the examined cases, the highest weighted cost increase appears in additives (ca. 8%), followed by electrical energy (ca. 2,9%). The decrease in raw materials cost (9,5%) is due to the significantly lower prices of recycled gypsum compared to conventional gypsum market prices, whereas the fluctuations in the remaining variable costs relate to the quality and properties of recycled gypsum in conjunction with the minor process adaptations implemented.

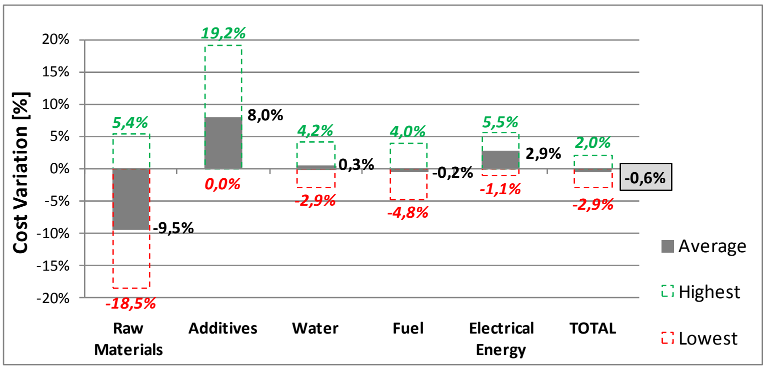

Figure 2 Average impact and range of impact of recycled gypsum use maximization on variable costs of plasterboard manufacturing

The range of variation per cost element (highest and lowest %) illustrated in Figure 2 is markedly broad and the apparent conflicting trends in almost all the cost elements that range from positive to negative effects clearly indicate the dependence of the results on specific process characteristics. The clearest trend appears in the cost of additives, which is rather expected; due to changes in the characteristics of the feedstock mix, the properties of the stucco slurry will 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. The inconsistencies depicted are attributed to the particularities of each pilot plant (i.e. differentiations in the base scenarios between industrial units) and clearly reflect the different technical adjustments made to each process in the 2nd round of trials. Nonetheless, the results for the net effect on total plasterboard cost show that all manufacturers managed to minimize the impact caused by the increased incorporation of recycled gypsum by appropriately and effectively adapting their processes.

Figure 3 shows the impact of recycled gypsum maximization on average energy consumption of plasterboard manufacturing process and the range of this impact in the five plants.

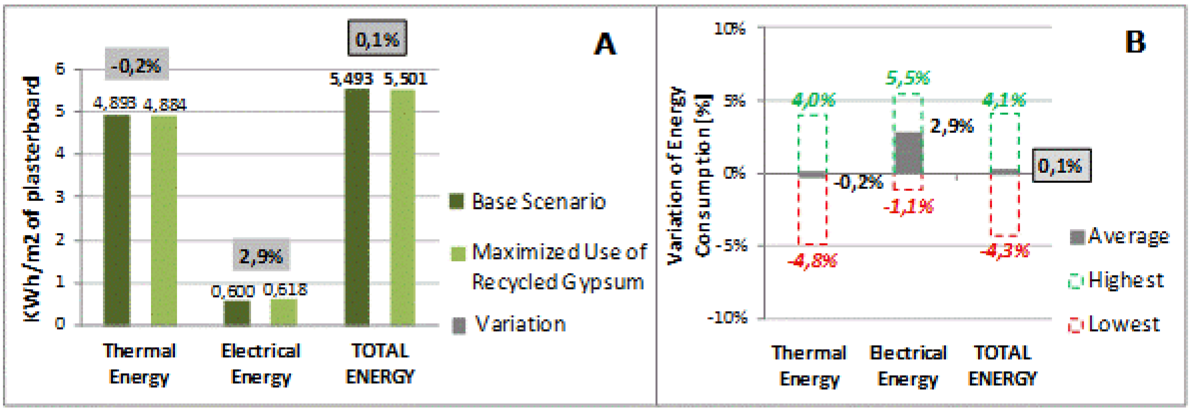

Figure 3 Impact of recycled gypsum use maximization on average energy consumption of plasterboard manufacturing process (A) and respective range of impact in the five plants (B)

As it can be seen, the energy analysis shows a marginal 0,1% increase in total energy consumption – indicative of the impact on CO_2 abatement costs – calculated as the net effect of small variations caused in the thermal and electrical energy consumption of the process.

In summary, the average cost of plasterboard and the calculated energy consumed in plasterboard manufacturing (~5,5 KWh/m^2 on average) remain almost invariable for both generalized scenarios. These figures do not include potential industrial equipment investments and modifications in the production lines that would be necessary in order to accommodate the increased flows of recycled material in the pre-processing stages. However, the assessed effects on individual cost elements confirm that the properties of recycled gypsum directly or indirectly impact process costs.

Within the boundaries of uncertainty of the assessment, the calculated impact is too small to conclude a definite benefit or detriment in energy consumption and related costs when increasing the content of recycled gypsum up to ca. 30% in Type A plasterboard production. Potential savings or losses lie within the estimated uncertainty thresholds.

Aside from the uncertainties, Figure 4 illustrates the combined influence of fluctuations in the market prices of conventional raw materials and chemical additives based on a sensitivity analysis performed for the average results for the two generalized scenarios, highlighting the combination of conditions under which neutral or even greater positive impact on plasterboard cost can be achieved. Namely, Figure 4 shows cases where potential increases in the prices of additives are amortized if rises occur in conventional gypsum prices, which favour the high use of recycled gypsum. Other than that, the impact of recycled material re-incorporation on plasterboard cost is not considered particularly sensitive to the prices of water, fuel and electricity.

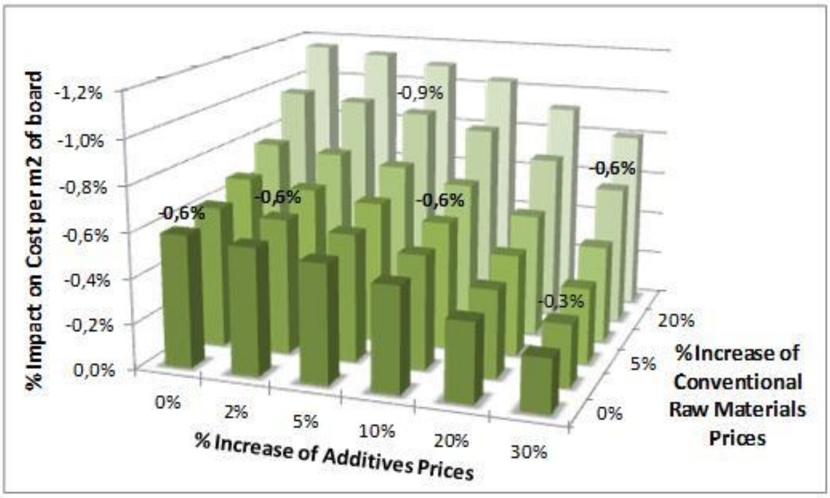

Figure 4 Impact of price increases of conventional gypsum and additives on the cost of plasterboard with high recycled gypsum content

Based on the results of the sensitivity analysis, it can be concluded that the use of recycled gypsum at high levels is favourable to potential market price increases of conventional raw materials.

<u>**Conclusions**</u>

The work carried-out fulfilled the goal & objectives of Action B3. Overall, the GtoG trials:

- Proved that **re-incorporation (up to 30%) of recycled gypsum in Type A plasterboard manufacturing is feasible in practice**, even under the adverse conditions of non-permanent process adjustments. The GtoG 30% target was fully reached in 2 out of the 5 plants. For the examined cases, the net average impact on the total variable manufacturing cost and energy consumption per m^2 of plasterboard was found to be practically negligible taking into account the uncertainty margin of the assessment, the current market prices and quality characteristics of recycled gypsum. Potential cost benefits were levelled, mainly due to the requirement of higher amounts of relatively costly additives. 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 fee for land-filling). Stronger economic and environmental benefits can arise in the future, when the necessary process modifications will be optimised and the recycled material quality will consistently rely with the quality specifications set by the GtoG project.

- Proved that the reincorporation of recycled gypsum up to 30% does not noticeably affect the basic **performance characteristics of Type A plasterboards**; all samples were found to conform to the EN-520 Standard. GtoG made possible the collection and analysis of a significant number of recycled material and plasterboard samples from different origins, which otherwise would not have been feasible.
- Highlighted **potential production bottlenecks in terms of recipe modifications** (e.g. in additives) **and production process equipment** (e.g. storage, feeding conveyors, recycled gypsum pre-processing etc) that may arise when the increased percentage becomes standard practice in the plasterboard manufacturing. The analysis of the impacts on individual process parameters and cost elements indicated dependence on specific feedstock and process characteristics. The outcome of the production trials allows each manufacturer to develop plans for the relevant and necessary industrial adaptations, which are costly and require further trials and time.
- Demosntrated in practice **the full engagement of plasterboard manufacturers** to develop recycling practices that will permit higher re-incorporation percentages in the future. For the first time, and in the frame of Action B3 of GtoG, the plasterboard manufacturing industry performed controlled and synchronized production trials in five different plants in four European counties.

The overall findings and the collective knowledge-experience obtained by the manufacturers are promising and permit planning of future investigations even at higher re-incorporation percentages, above the 30% target of the GtoG project.

Recommendations & Future Steps

The conditions of the present research (five plants with different sources of conventional and recycled material and manufacturing practices) did not allow the assessment of the impact of specific recycled gypsum characteristics on the process parameters. The latter was, in any case, beyond the scope of the study that focused on the techno-economic impact of increased re-incorporation level.

However, the specifications of recycled gypsum and the consistency of its characteristics can be anticipated to play a critical role in maintaining the plasterboard quality (compliance with EN-520 Standard) with minimum process adaptations.

Due to the individualized procedures followed at each plant, GtoG cannot develop a generalized methodology, including standardized plant modifications, for the optimum/highest inclusion percentage of recycled gypsum in the plasterboard manufacturing process. However, the experience acquired can provide important guidelines for future investments and validation production trials.

In this context, purity is reported as a potential restriction with regards to increasing the level of recycling to higher percentages. Locality could favor recyclers to meet particular purity specifications, since manufacturers of a certain geographical area are likely to receive post-consumer recycled gypsum originating from their own products. Further studies are needed to assess quantitatively the implications of recycled material purity.

Residual paper content is also pinpointed as an important re-incorporation limiting factor. Specifications on TOC should be kept particularly low (< 1%), because in the long-term post-consumer recycled gypsum will originate from plasterboards with already high content of recycled material, thus continuously raising TOC levels. A specification for the maximum acceptable size of paper pieces to the example of the related British standard PAS 109 is also considered highly required.

The presence of silicones in the recycled material is considered to pose a measurable risk, depending on the type of board manufactured. The further investigation of the inclusion of such recycled material in the process and a related specification is thus recommended. The proposal of a monitoring methodology for silicones is beyond the scope of this report.

In order that re-incorporation at the project's target rate of 30% becomes standard practice, the recycled material volumes required for constant dosage supply need to be available and investment for process upgrades (e.g. storage, feeding conveyors, recycled gypsum pre-processing set-up etc.) from the manufacturers' part will be required. The feasibility of continuous and systematic provision of the amount of recycled material necessary to meet production needs must be assessed by both recyclers and manufacturers.

In any case, as long as the incorporation of recycled gypsum in the manufacturing process is established at high levels on a constant basis or even further increased (e.g. up to 50%), the recycled gypsum specifications will probably have to be revised in the future; recyclers may have to seek and implement more sophisticated decontamination techniques and/or waste sorting methods and criteria for reclaim, as already suggested by the manufacturers, and minimize fluctuations in the characteristics of the recycled material.

The assessment of the impact of high re-incorporation rates of recycled gypsum *on a constant basis* through more test productions, the parametric investigation of the impact in relation to the basic properties of recycled gypsum (moisture and purity), the expansion of the study's scope to include more technical boards and other gypsum-based products and a mapping of sources with quantitative estimation of recycled material that might become available at national/ EU level could be the objects of further work in the future.

Glossary

The glossary refers to definitions of terms *as used in this report*.

Anhydrite

The chemical compound calcium sulphate (chemical formula $CaSO_4$), the dehydrated state of gypsum. It is found in nature as a mineral, but it can be also produced industrially when gypsum is calcined to temperatures above 180°C (soluble anhydrite) and up to 540°C (insoluble anhydrite or commonly called “dead-burnt gypsum”).

Calcination

Industrial thermal process intended to produce physical or chemical changes in certain raw materials. In the gypsum industry it refers to the process in which the dihydrate content of gypsum changes hydration state by partly or completely releasing its crystal water, depending on the chosen method and conditions (temperature, pressure). In plasterboard manufacturing the term refers to the production of β-hemihydrate ($CaSO_4.1/2H_2O$).

Conventional Gypsum

Gypsum derived from conventional sources (i.e. non-recycled). Includes natural gypsum, FGD and other types of synthetic gypsum (titanogypsum, citrogypsum etc.)

Deconstruction

Demolition carried out with organized and controlled methods (such as selective stripping-out of elements and materials and on-site segregation of waste) aiming at the recovery of mono-streams of building materials, thus facilitating and increasing their recyclability, as opposed to uncontrolled demolition that generates a non-homogenous heap of damaged materials.

Dihydrate

The chemical compound calcium sulphate dihydrate (chemical formula $CaSO_4.2H_2O$) which is the predominant component in all types of gypsum. When heated at higher temperatures it changes hydration state and converts to hemihydrate or anhydrite depending on the temperature range.

FGD Gypsum / DSG

Type of synthetic gypsum obtained as a by-product from the wet Flue Gas Desulphurization (FGD) process of fossil fuel-fired power stations, widely used for plasterboard manufacturing. Also referred to as DSG (Desulphurized Gypsum).

Gypsum

Material that predominantly contains calcium sulphate dihydrate extracted from quarries in mineral form, produced synthetically or sourced from the recycling of gypsum-based waste.

Gypsum Recycling

The controlled processing of gypsum-based waste to produce recycled gypsum. The recycling process includes crushing, separation of paper from the gypsum core of plasterboard, manual and/or mechanical removal of impurities and physical contaminations such as metallic and wooden parts, coatings, coverings, insulation, etc. when present and fine grinding of gypsum.

Hemihydrate

The chemical compound calcium sulphate hemihydrate (chemical formula $CaSO_4.1/2H_2O$) which is the primary component of stucco used in plasterboard manufacturing. It is produced from calcium sulphate dihydrate ($CaSO_4.2H_2O$) when heated in the temperature range of 120-170^{o}C. Also commonly called “plaster of Paris”.

Internal Recycling

The processing of gypsum-based waste to produce recycled gypsum carried out at recycling facilities owned by the plasterboard manufacturing plant, usually located at the plant site.

Natural Gypsum

A common soft sulphate mineral mainly composed of calcium sulfate dihydrate that exists as a natural resource and is extracted from the ground. Its purity varies depending on the deposit and the rest consists of other generally inert minerals such as clays, sand, anhydrite, dolomite and limestone. Also referred to as “Mineral Gypsum”.

Plaster

Gypsum subsequently undergoes several preparatory and production phases including calcination to produce plaster, a dehydrated form of gypsum, which is further used in the production of a variety of building materials including plasterboards.

Plasterboard

Plasterboards (also referred to as “Gypsum Boards”, “Drywall”, “Wallboards”) are flat rectangular building boards consisting of a plaster core whose surfaces and longitudinal edges are paper-covered and profiled to suit the intended application. The paper-covered plaster core can contain additives to achieve certain properties. According to EN 520 the different types of plasterboard with regard to their properties that are manufactured for specific uses are designated by correspondingly assigned code letters. The contents of the present report refer to the “Standard” plasterboard Type A.

Plasterboard Production

In general the term applies to the complete plasterboard manufacturing process, from the handling of gypsum feedstock until the finished product at the end of the board line. In the present report it refers to the second continuous step of the two-step process of plasterboard manufacturing, which starts with the mixing of the stucco slurry, includes paper feeding, setting, cutting and drying of plasterboards and ends at the exit of the drier. The process’ first step is “Stucco Production”.

Post-consumer Gypsum-based Waste

Gypsum-based waste generated by households or by commercial, industrial and institutional facilities in their role as end-users of the gypsum product that can no longer be used for its intended purpose (based on the definition of post-consumer material of EN ISO 14021). The term practically refers to gypsum waste from construction (off-cuts, damaged plasterboards etc.) and demolition/deconstruction sites.

Post-consumer Recycled Gypsum

Recycled gypsum derived from post-consumer gypsum-based waste.

Production Waste / Pre-consumer waste

Plasterboard waste generated from the manufacturing process after quality inspections as out-of-specification boards, failing to meet the set quality standards. They are usually re-processed at the plant site and recycled into the process as "production recycled gypsum". Alternatively they can be sent to an external recycler. Also referred to as "Production Rejects".

Production Recycled Gypsum

Also referred to as "Pre-consumer Recycled Gypsum". Gypsum powder derived exclusively from recycling plasterboard waste generated from the plasterboard manufacturing process. In this report the term refers to gypsum from production waste processed at the manufacturing plant's own recycling facilities.

Purity

The $CaSO_4.2H_2O$ content (% w/w on a dry basis) of gypsum.

Recycled Gypsum

Gypsum in powder form produced by the recycling process of gypsum-based waste, that can be used as a raw material in the plasterboard manufacturing process substituting conventional gypsum. In this report the term refers to the mixed stream of production and/or post-consumer recycled gypsum introduced in the feedstock mix for the production of plasterboard.

Recycler

A company that specializes in the processing of gypsum-based waste to produce recycled gypsum.

Setting

The rehydration of stucco back to gypsum according to the reverse reaction of calcination; the hemihydrate contained in the stucco converts to crystalline dihydrate. During the setting of plasterboards the bond between the paper and the plaster core is formed by the growth of gypsum crystals into the fibrous pores of the paper.

Stucco

A form of plaster, the product of gypsum calcination. The term refers to the intermediate product in the plasterboard production, whereas plaster is an end product for the construction market. In the manufacture of plasterboards it mainly consists of β-hemihydrate.

Stucco Production

The first step of the two-step process of plasterboard manufacturing, which comprises the pre-processing stages of gypsum feedstock and calcination.

Synthetic Gypsum

Gypsum produced as a by-product from various industrial processes. The most widely used type in plasterboard manufacturing is FGD. Other types include titanogypsum, citrogypsum, phosphogypsum etc., their potential suitability depending on quality and cost.

1. Introduction

1.1 Aim and Scope

The present report refers to the results of GtoG Project's Action B3 – "Towards Sustainable Lightweight Systems" which aims to identify the crucial parameters of the plasterboard manufacturing process affected by the use of recycled gypsum as feedstock and to assess and quantify the resulting impact on product quality and on the process' energy consumption and variable production costs.

Gypsum products are indefinitely and 100% recyclable as they always keep their natural properties during use. Most plasterboard manufacturing plants already recycle their own production waste. This results in up to ~5% inclusion of re-processed secondary gypsum as raw material in the board. Moreover, some plants have recently started to introduce the usage of recycled post-consumer gypsum-based waste (i.e. from construction and demolition/deconstruction sites) raising the above percentage to ~10-15%.

Recycled gypsum derived from production waste is free of impurities (except for the residual paper originating from plasterboard waste), as opposed to the post-consumer recycled material which can contain various traces of impurities such as wood pieces, metal parts, paints, adhesives etc. originating either from the board's application as a product or/and the handling practices of plasterboard waste at the demolition or construction site. Furthermore, the generated volumes of post-consumer gypsum-based waste are becoming increasingly larger and are expected to further increase in the future, given the widespread usage of plasterboard in modern constructions.

The challenge addressed in the GtoG project is to deal with more complex raw material of variable quality without relying on landfill by re-incorporating more into plaster-based products, and to reach the target of 30% recycled gypsum in the board, by increasing the amount derived from construction and demolition/deconstruction waste. The technical feasibility of this target is investigated in the framework of Action B3 of GtoG.

Action B3 is divided in two closely-linked sub-actions which ran in parallel. Sub-action B3.1 involved demonstration projects (i.e. production trials) in five plasterboard manufacturing plants located in Germany, France, the UK and Belgium. The production trials were realized in two rounds, aiming to identify the bottlenecks hindering the incorporation of recycled gypsum up to the set target of 30% and to define solutions and necessary technical changes in order to adapt the process and facilitate increased recycling. The percentage of recycled gypsum usage was gradually increased to reach the allowable maximum for maintaining given product quality standards. During the trials samples of the raw materials (conventional as well as recycled gypsum) and of the obtained products (plasterboards) were taken for property analysis in order to assess the impact on feedstock and product quality. Furthermore, the important technical parameters of the process were recorded (material and energy flows, process conditions etc.) and these data were used as input for the techno-economic assessment of the impact of the maximized usage of recycled gypsum in plasterboard manufacturing, which was the objective of Sub-action B3.2.

The obtained results of Action B3 of GtoG based on the above mentioned production trials are presented in this deliverable report and include the following:

- the important parameters of the plasterboard manufacturing process affected by the increased use of recycled gypsum as identified during the pilot trials,
- the property analysis results of the raw material and product samples collected,
- the results of the techno-economic analysis focusing on the impact of recycled gypsum's usage maximization on the process' energy consumption and costs.

1.2 Partners of Action B3

The group of partners participating in Action B3 of GtoG consists of 5 plasterboard manufacturing companies and 2 academic institutions. The detailed list of partners with respect to Action's B3 structure is shown in Table 1-1.

Table 1-1 Structure and list of partners of Action B3

Action B3	**Towards Sustainable Lightweight Systems**
Action Leader	**KNAUFKG**
Sub-action B3.1	Gypsum Waste Recycling – Technical Feasibility – Process Adaptation
Coordinator	Knauf Gips (KNAUFKG)
Partners	Siniat FR (L1)
	Siniat Ltd UK (L2)
	Saint-Gobain Placoplatre (SG1)
	Saint-Gobain Construction Products Belgium NV – Gyproc (SG2)
	Fundacion General Universidad Politecnica de Madrid – Official Laboratory for Testing Materials of Construction (LOEMCO)
Sub-action B3.2	Economic Evaluation – Energy and Raw Material Saving Potentials
Coordinator	Siniat FR (L1)
Partners	Knauf Gips (KNAUFKG)
	Siniat Ltd UK (L2)
	Saint-Gobain Placoplatre (SG1)
	Saint Gobain Construction Products Belgium NV (SG2)
	National Technical University of Athens (NTUA)

1.3 Connection with Other Actions of GtoG Project

Action B1 of GtoG deals with the optimization of current practices, as identified in Action A1, in the deconstruction and segregation of lightweight gypsum elements from construction and demolition waste and involved a series of deconstruction pilot projects. Furthermore, Action B2 addresses the issues of optimization of methods and practices in order to obtain clean recycled (processed) gypsum with properties similar to conventional gypsum, thus enabling its easier incorporation in the manufacturing process and the establishment of the end-of-waste status for recycled gypsum. The combined implementation activities of Actions B1 and B2 ensured delivery to the gypsum board manufacturers of homogenized recycled material, free of contaminations, which met their required specifications and was therefore suitable for use in the production trials. In this manner Action B3 integrates the achieved results to demonstrate, at industrial level, the optimized value chain.

The results of Actions A and B were used in Action C1 for the establishment of representative best practice indicators for each step of the value chain to be used for monitoring and for the quantified assessment of potential value chain modifications.

It is noted that the consortium of partners of the GtoG Project includes 17 stakeholders that cover the entire value chain of gypsum boards and consists of 5 demolition companies, 1 demolition consultancy firm, the 2 major European gypsum recyclers, 5 gypsum board producers, 3 academic institutions and Eurogypsum. The overall project's structure and time plan is shown in Figure 1-1.

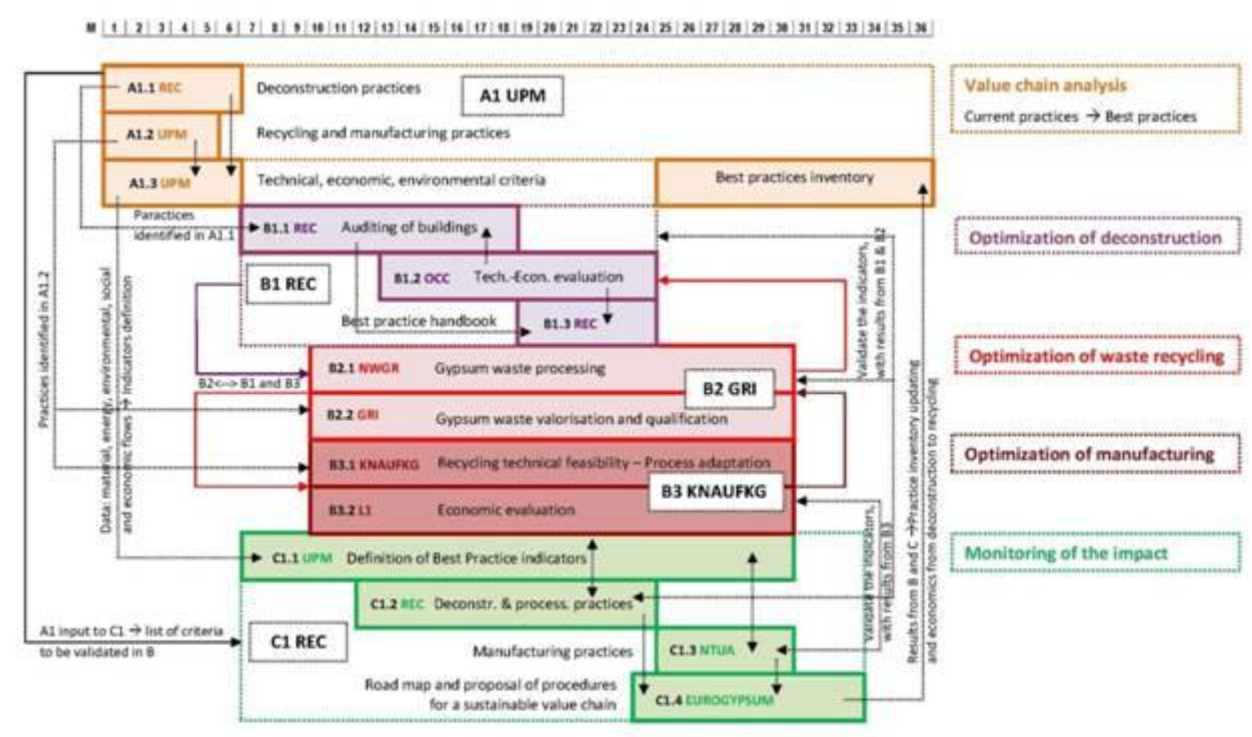

Figure 1-1 GtoG Project structure and time plan

2. Implementation Approach of GtoG Project Action B3

2.1 Pilot Projects

In the framework of Sub-action B3.1 five pilot projects took place in the five participating plasterboard manufacturing plants located in Germany, France (2 plants), the UK and Belgium. Within the scope of Action B3 the main objectives of the pilot projects were:

- to identify the existing bottlenecks that hinder the intended considerable increase of recycled gypsum usage,
- to investigate potential solutions to overcome these bottlenecks and to reach a maximum recycled gypsum percentage up to the GtoG's set target of 30%,
- to determine, after testing in practice, the necessary technical changes and modifications in the manufacturing process, and
- to assess the resulting impact on the manufacturing process in terms of product quality, energy consumption and variable costs.

The pilot projects involved a series of production trials carried out in two parts as described in the following sections.

2.1.1 Pilot Plants

The selected plants produce plasterboard using typical production lines. The typical production steps that include calcination, storage of stucco, blending, setting, cutting and drying are therefore common in all plants, but the processes are not identical. Differences exist in the feedstock/feedstock mix used and consequently in the raw material pre-processing stages (grinding, sieving, pre-drying etc.) which mainly depend on its type and properties, as well as in the industrial equipment employed. This fact is considered positive for the project's purposes since it provides a broader range of sample cases.

The planned production trials were carried out in the following plants.

- **Knauf Gips KG, Iphofen, Germany**. It is the headquarters of the KNAUF Group (group of companies). The plant currently already uses gypsum from production rejects, recycled at its own facilities (recycling line). Post-consumer recycled gypsum has not been introduced to the process yet. The plant's location provides easy access to recycling plants. The post-consumer recycled gypsum for the 2nd trials has been provided by Gypsum Recycling International (GRI), one of the partners of the GtoG.
- **Siniat Ltd UK, Bristol Plant, Bristol, UK**. The plant has already long-term experience regarding recycling and usage of gypsum waste; the plant already recycles production and post-consumer recycled gypsum; however, to a significantly lower percentage than the GtoG target. The post-consumer recycled gypsum is obtained from a variety of industrial partners, including one of the partners of GtoG, whereas production waste is recycled at the plant site.
- **Siniat FR, Auneuil Factory, Auneuil, France**. This plant is located in the north of Paris. Natural gypsum supplied by road. The production capacity has been increased recently to face the local

market expansion. This plant already recycles plasterboard production rejects, as well as post-consumer gypsum waste coming from construction and demolition sites at its own recycling facilities. The total percentage of recycled gypsum is significantly less than the GtoG target.

- **Saint-Gobain Placoplatre, Vaujours Factory, Vaujours, France**. The plant already uses post-consumer recycled gypsum from construction and demolition waste delivered by contracted collectors according to specifications. The recycled gypsum is supplied by NWGR, which also processes (recycles) the plant's production waste. The total percentage of recycled gypsum is significantly less than the GtoG target.
- **Saint-Gobain Construction Products Belgium NV, Divisie Gyproc, Kallo, Belgium**. The Gyproc plant at Kallo already uses post-consumer recycled gypsum from construction and demolition waste in limited quantities. The recycled gypsum is supplied by NWGR, which also processes (recycles) the plant's production waste. The total percentage of recycled gypsum is significantly less than the GtoG target.

2.1.2 Production Trials

The production trials took place from January 2014 until March 2015, spread over several months to eliminate risks regarding production output and the overall normal commercial operation of the pilot plants. This approach also served the opportunity to make more radical process interventions between trials, should these be required.

As already mentioned, the trials were carried out in two parts.

A. Base Scenario – 1st Round of Production Trials

The 1st round of trials (January 2014 – July 2014) refers to a series of runs *of the standard production* in each plant, which included all the different raw material streams and the standard percentage of recycled gypsum (production and post-consumer if already introduced) in the feedstock mix. The purpose of these trials was to record a defined set of technical and economic parameters of the current process, which would serve as *Base Scenario* in order to investigate and quantify the impact of the intended increase in the percentage use of recycled gypsum.

The implementation strategy initially discussed at the beginning of Action B3 was to carry out production trials in three rounds, where the 1st round would involve gypsum feedstock exclusively from conventional sources as a basis for assessment. However, the industrial partners considered this approach impractical from a technical point of view, and, furthermore, a "step backwards" from the so far achieved progress towards recycling.

In the adopted approach, given that the majority of the pilot plants have already introduced to a certain extent the usage of post-consumer recycled gypsum in their standard process, the starting point for reaching the target of 30% was different for each plant. More importantly, the principal bottlenecks that set back the further increased use of recycled material had been identified and certain process parameters had been possibly modified according to each plant's feedstock mix. However, the manufacturers address these issues on a case-to-case basis and the adjustments made are considered process-specific for each individual plant. The goal of the trials is to end up with generalized qualitative as well as quantitative results that provide guidelines to establish the optimized high recycling process as a widely implemented practice outside the group of the five participating plants, by quantifying the impact of maximizing the use of recycled gypsum and identifying all existing setbacks. In this context the adoption of the "business-as-usual" base scenario for the 1st round of test productions helps to derive as much experience as possible from this project.

B. Recycled Gypsum Use Maximization – 2nd Round of Production Trials

The 2nd round of trials (October 2014 – March 2015) involves repeated test productions with gradually increasing amounts of recycled gypsum above the current standard (if any) amount used and up to the set target of 30% or up to a technically feasible maximum, given either by product quality and/or process efficiency according to process-specific technical features. The aim was to reach the maximum by increasing *the percentage of post-consumer recycled gypsum* (derived from construction and demolition waste from various jobsites) and keep the same percentage of production recycled gypsum as in the 1st round of trials.

The percentage of recycled gypsum at each increment of increase was confirmed by checking the consistency of the production runs. The consequent process effects as well as the respective controlling actions taken to restore process stability were recorded. The vital technical and economic parameters as defined in the 1st round were also recorded for the purposes of the energy and techno-economic analysis. No "hardware" production process modifications (i.e. incorporation of new equipment) were to be realised at this stage. Modifications may include changes in material feed rates, setting times, calcination temperatures etc.

The general criteria set for determining the maximum introducible amount of recycled material include:

- Board production without problems
- Plasterboards to fulfil quality requirements (EN 520 standard and/or any other specifications)
- Other restrictions (i.e. impact on production rate, significant increase in energy consumption, economic feasibility etc.)

Apart from the above general guidelines, the pilot plants followed their own specific procedure for maximizing the recycled gypsum percentage (i.e. number and size of increase steps, duration of test productions, product quality thresholds etc.) according to the individual characteristics and requirements of each process and production line.

2.2 Data Collection

The findings of this report are based on data mainly obtained from the production trials. The collected data were drawn from three sources:

- the receipt of samples of raw materials and products for property analysis
- the systematic recording of the techno-economic parameters of the plasterboard manufacturing process
- ground observations.

2.2.1 Receipt of Samples

Samples of the raw materials used (both conventional and recycled gypsum), of the stucco produced and of the final plasterboard were taken from every production trial and sent for property analysis by LOEMCO. Details on the number and types of samples and the methods employed for the analyses are given in Chapter 5.

2.2.2 Recording of Techno-economic Parameters of the Manufacturing Process

For the recording of the key techno-economic parameters of the process a set of data templates developed by NTUA (responsible for the techno-economic assessment in the framework of Sub-action B3.2) were distributed to the industrial partners to be filled-out during the two rounds of trials. Even though the templates referred to the same types of data, the required inputs were adjusted to each individual process' characteristics and regular practices. This allowed the systematic quantitative recording of a defined set of parameters and at the same time facilitated the filling-out procedure and ensured the validity of the collected data.

Overall the templates covered the manufacturing parameters affected by the use of recycled gypsum per stage of the plasterboard production process, within the scope of the techno-economic assessment (see Chapter 6). The list of inputs specifically includes:

- raw material transportation data (e.g. distances, means etc.)
- raw material basic composition properties (free moisture content, purity, main impurities)
- material consumptions (gypsum, stucco, facing paper, additives)
- water consumption
- thermal energy consumptions per process stage (fuel types and consumptions)
- electrical energy consumptions per process stage
- product mass flows
- process waste streams and mass flows
- temperature and pressure data for calcination and plasterboard drying stages
- cost data.

The set of parameters under study was selected so that all effects resulting from the increasing use of recycled gypsum in the course of the trials reflected, directly or indirectly, on the recorded changes of their values (e.g. the impact on energy consumption, water demand etc. is directly evident by comparing the 1st and 2nd round of trials' data, whereas possible changes/adjustments in the recipes to overcome implications in the setting of stucco slurry reflect on the change of the mass flows and/or cost of the additives mix). In this manner, the data gathered enable the quantitative assessment of the impact of the use of recycled gypsum in relation to its basic properties on the process' energy consumption and variable costs.

2.2.3 Ground Observations

Ground observations refer to the directly observed practical impacts of the increased use of recycled material on the process during the test productions. The recording of this impact expressed as eventual problems in production (such as paper delamination, bubbles in core, quality of wet cut, changes in setting time of the stucco slurry, drying characteristics, edge quality etc.) provided the feedback in order to link these effects with the specific characteristics of the recycled gypsum feedstock that hinder the maximization of its use to the desired level. The process modifications made to overcome these problems were also recorded. This was done systematically with questionnaires (see Appendix I) filled-out by the industrial partners after the 2nd trials. The requested inputs in the questionnaires include the description of the difficulties/problems encountered during the 2nd trials, the process adaptations and equipment modifications needed to overcome these problems and the listing of all potential re-incorporation issues.

Furthermore, during June 2014 the NTUA team visited the five pilot plants after the completion of the 1st round of production trials and before the 2nd round. The purpose of these organized visits was to clarify ambiguities in relation to the production practices at each plant and issues regarding the data collection process (data templates) and to facilitate the accurate recording of key techno-economic parameters, given each plant's individual process characteristics.

2.3 Overall Implementation Approach

Action B3 is divided, as already mentioned, in two closely linked sub-actions; the pilot projects conducted in the framework of Sub-action B3.1 provided the input for the cost effectiveness and energy analysis in parallel with the technical developments, which is the object of Sub-action B3.2. The structure and implementation approach of Action B3 is shown in Figure 2-1.

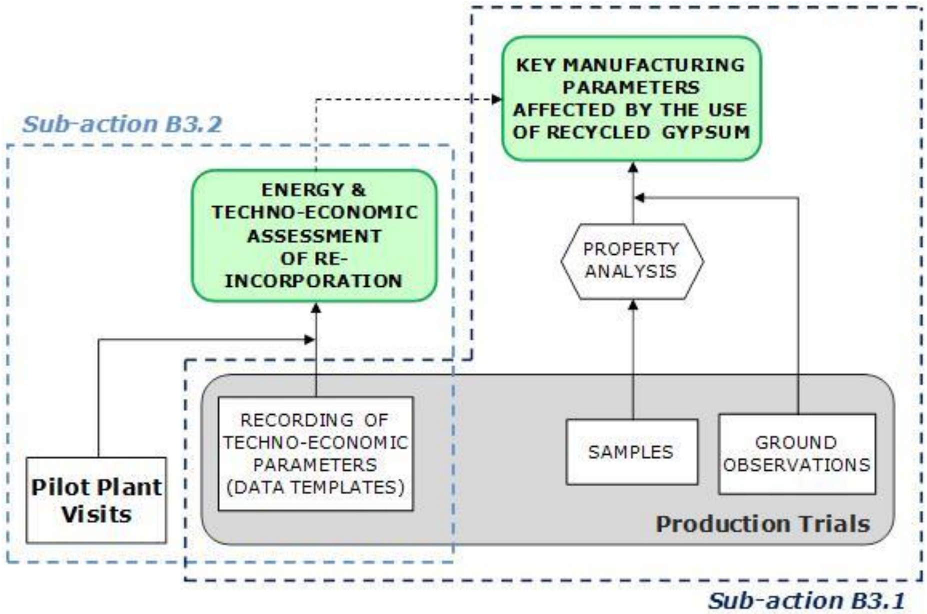

Figure 2-1 Structure and implementation of Action B3

The identification of the key plasterboard manufacturing parameters affected by the increased use of recycled gypsum is based on the co-assessment of ground observations with the results of property analysis of raw materials and products. More specifically, the property analysis of the raw materials shows the differences between the standard and the increased recycled gypsum feedstock mix. The assessment of these differences in relation to the observed process implications during the trials results in linking specific quality characteristics of recycled gypsum to the respective process effects caused by the change. Accordingly, the property analysis of product samples (plasterboard) helps to evaluate the effectiveness of the modifications and adaptations made to the process by confirming the consistency in product quality and the compliance with the required quality standards and provides the guidelines to further optimize the process with the established recycled gypsum usage maximum, if needed. These results also contribute to the determination of the minimum required specifications that the recycled material has to fulfill in order to be re-incorporated in the plasterboard production process.

The recorded techno-economic parameters of the process are used as input for the energy and techno-economic analysis of recycled gypsum’s re-incorporation into the process. The results of the analysis also contribute, in turn, with some valuable insights in the determination of the key manufacturing parameters.

3. Plasterboard Manufacturing Process – State Of The Art

Gypsum plasterboards are flat rectangular building boards consisting of a plaster core whose surfaces and longitudinal edges are paper-covered and profiled to suit the intended application. The paper-covered plaster core can contain additives to achieve certain properties. Plasterboards are used in a broad range of building applications, especially as wall and ceiling linings, as well as for the manufacturing of prefabricated building components. [1,2]

Plasterboards are manufactured in a two-step process. The first step's generic stages include pre-processing of the gypsum feedstock (size reduction and pre-drying depending on feedstock type and properties), followed by the thermal process of calcination. The intermediate product is stucco, a partly dehydrated form of gypsum, which is then mixed with water and additives to form the plaster slurry. The slurry is fed to the board line where it is encased between two layers of special strong paper and gradually sets while it is conveyed along the line at an appropriate speed. When set, the continuous length of plasterboard is cut to individual uniformly sized boards, which proceed to a large multi-zone drier to remove the excess free water and exit as the finished product.

3.1 Raw Materials

The feedstock mix for the production of stucco may consist of one or more types of gypsum from conventional sources (natural and/or synthetic). Traditionally, most plants that introduced synthetic gypsum into their process used it in a mixture with natural ore, but today there are many modern plants that manufacture plasterboard exclusively from synthetic gypsum [3].

Feedstock can also contain a percentage of recycled gypsum derived from production waste and/or post-consumer gypsum-based waste from construction and demolition/deconstruction jobsites.

In any case, each individual gypsum type as well as its source must be assessed regarding its particular suitability for plasterboard manufacturing, which may vary depending on purity or other technical and toxicological parameters of the material.

3.1.1 Natural Gypsum

Natural gypsum is a soft rock-like sulphate mineral predominantly composed of calcium sulfate dihydrate (chemical formula $CaSO_4.2H_2O$), formed geologically from the evaporation of super-saturated aqueous solutions resulting in the sedimentary deposition of calcium salts in large basins (former shallow seas). The earliest deposits date to around 200 million years ago. [4]

Gypsum rocks differ in their degree of purity ($CaSO_4.2H_2O$ % w/w content), colour and structure based on their geological history [1]. Depending on the deposit, purity varies between 75 and 95% [4], the remainder being other generally inert minerals such as clays, sand, anhydrite, dolomite and limestone [1]. The mineral anhydrite (chemical formula $CaSO_4$) is the un-hydrated form of gypsum. It has a very different structure which makes it comparatively limited in its technical applications [1,2,4] and its presence in the rock as a raw material for plasterboard production is mainly considered undesirable.

The color of gypsum rock is usually white, but it can also be colorless, grey or shades of red, brown and yellow, being naturally influenced by the types of impurities contained [1,5]. Rock size may reach up to 50 cm in diameter.

Gypsum is a common mineral abundantly found in many countries of the world. The top three worldwide crude gypsum producers are China, Iran and USA, while the principal gypsum deposits in Europe are located in Spain, Italy, Russia, France, Germany, Poland, the UK, Romania, and Ukraine [5]. It is extracted from open-cast –which is primarily the case in Europe– or underground mines, using specific drilling machinery and non-polluting explosives [2,5].

3.1.2 Flue Gas Desulphurization Gypsum

Flue Gas Desulphurization gypsum or FGD is the most widely used type of synthetic gypsum in the gypsum industry. It is obtained as a by-product from the wet flue gas desulphurization process typically used for cleaning the emissions of power stations fired with fossil fuel (e.g. coal). The combustion flue gases are washed in scrubbing towers in counterflow with an aqueous suspension of finely powdered limestone or lime. The contained SO_2 is removed from the flue gas by the water and reacts with the alkaline suspension to calcium sulphite, which is subsequently oxidized with atmospheric oxygen and precipitates as calcium sulphate dihydrate ($CaSO_{4.}2H_2O$) crystals, i.e. gypsum. The gypsum is separated from the suspension, washed with clean water to remove the water soluble impurities and finally dewatered with the aid of centrifuges or vacuum filters. [4,6]

FGD gypsum is a wet material in finely grained powder form, with a purity of >95%, considerably higher than that of most natural gypsums (typically ~80%) [1,5], the remainder being mainly unreacted calcium carbonate and traces of fly ash from the flue gases as impurities [3]. The differences between natural gypsum’s and FGD’s chemical composition and content of trace elements are minor and the homogenous grain size of FGD’s crystals provides a technical advantage for the production of many gypsum-based products compared to natural gypsum [1]. Moreover, due to its extremely high purity it can be blended with lower quality gypsum (natural or recycled gypsum of low purity) rendering exploitable for the manufacturing of gypsum products a material otherwise considered unsuitable [4]. It is therefore a commercial product and a directly usable raw material serving either as an alternative or as supplement to natural gypsum feedstock.

FGD gypsum is produced in most Western European countries, with around half the output coming from Germany [5].

3.1.3 Other Types of Synthetic Gypsum

Apart from flue-gas desulphurization, there are certain other industrial processes that produce gypsum as a by-product, obtained when calcium compounds react with sulphates or sulphuric acid. The principal, other than FGD, synthetic gypsum types potentially suitable for use in plasterboard manufacturing include titanogypsum (by-product of the sulphate process for titanium oxide production) and, to a lesser extent, citrogypsum (by-product of citric acid production process). Phosphogypsum (from phosphoric acid production) presents a higher level of natural radioactivity which is an important limiting factor for its extensive use [3,4].

The use of substitutes to natural gypsum reinforces the environmental-friendly profile of the gypsum industry since it both reduces pressure on natural resources and promotes the utilization of valuable materials that would otherwise end up in landfills. However, the potential suitability and usage of these types of synthetic gypsum for specific manufacturing applications highly depends on quality (impurities, structure, consistency etc.) as well as financial issues and in practice the quantities used are low [5]. Moreover, none of these materials are used in the production lines where the pilot projects of Action B3.1 were carried out and therefore they are outside the scope of this report.

3.1.4 Recycled Gypsum

Recycled gypsum is derived from gypsum waste (plasterboard, gypsum blocks, moulds etc.) generated from the manufacturing process and from construction and demolition/deconstruction jobsites (Figure 3-1). It is produced by controlled processing of these wastes to separate the gypsum, paper and any contaminants, so that it can be used as a substitute to natural or synthetic gypsum [2]. In fact, gypsum is amongst the few construction materials where "closed loop" recycling is possible, i.e. gypsum waste can be used to reproduce the same product [4].

Figure 3-1 Removal of plasterboards in a deconstruction jobsite (A), Post-consumer gypsum-based waste (B, C)

Once collected, the waste is recycled by specialized companies (i.e. recyclers). The recycling process includes crushing, mechanical separation of paper from the gypsum core of plasterboard and fine grinding of gypsum (Figure 3-2). The removed paper can be used in agriculture for fertilizers, mulch etc. For gypsum waste arising from demolition/deconstruction works which may contain a certain amount of physical contaminations such as metallic and wooden parts, coatings, coverings, insulation, etc. decontamination carried out either manually (most usually) during sorting of waste and/or mechanically during processing is necessary in order to achieve a high quality, pure recycled gypsum product. Modern recycling units are mechanically equipped to remove most of the impurities and foreign objects from the gypsum core.

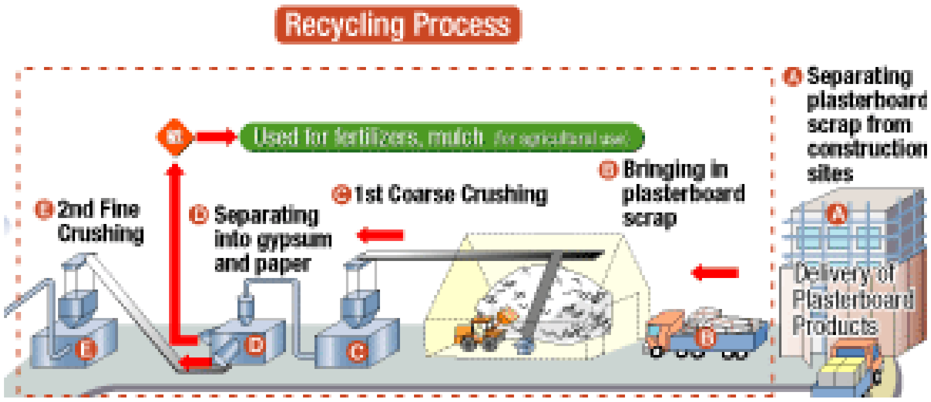

Figure 3-2 Gypsum recycling process

Recycled gypsum is usually in the form of a fine or sandy powder, or a small aggregate-type material [2]. Currently the quality requirements for recycled gypsum are 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.

Plasterboard waste from the manufacturing process are often recycled directly at the manufacturing plant and, given the relatively small percentage of production recycled gypsum incorporated in the feedstock mix, the waste may be simply crushed and ground without any paper separation taking place. Many plants equipped with a recycling line accept and process production waste from other plants and potentially post-consumer gypsum waste from jobsites, depending on their equipment's capacity and specifications. Manufacturing plants without recycling systems send their production waste to recyclers, who in some cases may operate recycling facilities located within manufacturing plant sites.

The recycling of production waste is traditionally a common practice and the inclusion of post-consumer recycled gypsum in the process is currently increasing, prompted by the need for compliance with legislative dictates as well as by potential economic benefits, given, of course, that it is not hindered due to technical reasons. In any case, recycled gypsum is introduced in a controlled blend into the manufacturing process as one single stream and not as separate streams depending on their sources. As an indicative example, this stream may consist of gypsum from internally recycled production waste and recycled gypsum received from a recycler.

3.2 Pre-processing of Raw Materials

The pre-processing of raw materials refers to the size-reduction (crushing and grinding) and pre-drying operations potentially carried out before calcination. These are directly related to the types and properties of raw materials, the specific process characteristics and the units of equipment employed at each manufacturing plant and therefore not all of the operations described below are performed at every plant. Indicative flowsheets for the overall stucco production process including pre-processing steps are given in Section 3.4.

3.2.1 Gypsum Rock Crushing

After extraction the natural gypsum ore must be crushed. Primary crushing aims at reducing the rocks to a size of about 5-10 cm or less in diameter and is carried out in suitable crushing machines such as jaw crushers (Figure 3-3A), roll crushers or impact crushers (Figure 3-3B) either at the extraction site or at the entrance of the plasterboard manufacturing plant. [5,6]

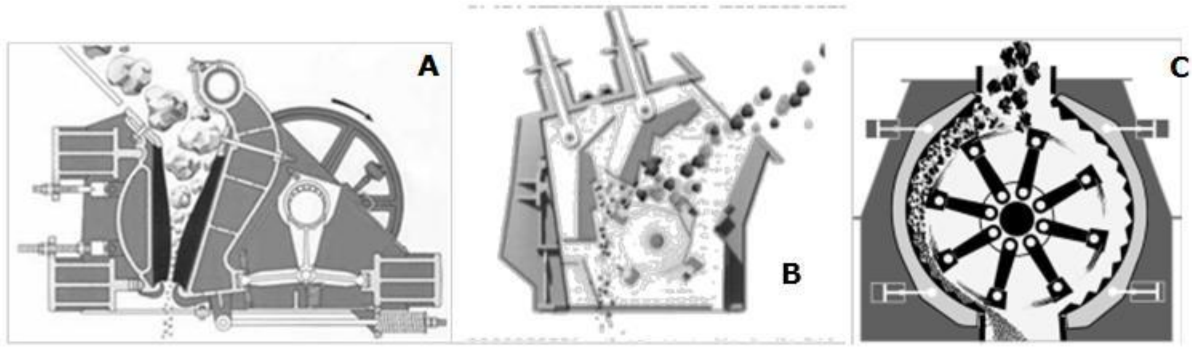

Figure 3-3 Types of crushers; Jaw crusher (A), Impact crusher (B), Hammermill (C)

Secondary crushing, if needed, further reduces rock size to around 2 cm and typically takes place in hammermills (Figure 3-3C) at the plant site [6]. The crushed rock is stockpiled and stored in covered spaces, preferably indoors to limit the absorption of humidity.

3.2.2 Grinding

In every process gypsum particle size must be controlled in order to obtain the exact properties required for the intended product. Moreover, depending on the method and unit of the subsequent calcination stage, a different grain size distribution might be necessary; for example coarser material can be calcined in rotary kilns, whereas fine-grained material is processed in kettles [1].

In many processes the crushed natural gypsum is finely ground to <200 μm in diameter in roller or other type of mills, which can be usually heated for simultaneous pre-drying of the material. In most modern plants grinding, pre-drying and partial or complete calcination of feedstock take place simultaneously in single units of equipment such as heated vertical roller mills, ring ball mills, impact mills etc.

The fine-grained FGD gypsum does not require grinding prior to calcination. Recycled gypsum is introduced at this point in the process, fed to the mill with the natural gypsum feedstock.

3.2.3 Pre-drying

Pre-drying refers to the removal of the free moisture contained in the gypsum feedstock, which is partly due to weather conditions (high air moisture, rain) while the materials are transferred and stored. High moisture hinders the "free" flow of the solid material and may lead to congestion of the equipment in the subsequent processing stages.

Natural gypsum has normally 1-3% free moisture content when extracted [6] and is typically pre-dried during grinding in heated mills. The heat is provided by incoming hot gas at the bottom of the mill from burners and/or recovered flue gases from calcination. The hot gas contacts the gypsum directly as it is ground, dries it and conveys it to a separator (i.e. cyclone or filter) for collection.

In processes relying on non-heated grinding mills and/or if the moisture content of gypsum is higher (e.g. if the material has been stockpiled outside) drying in order to reduce moisture below normal levels is required and is carried out after the crushing stage in directly heated rotary dryers. [6]

Regarding FGD gypsum, due to its production methods (i.e. dewatering in centrifuges and filters) its moisture content ranges between 8-10% when delivered to the gypsum plants and it must be dried prior to calcination, typically in flash dryers or other type of dryers (e.g. fluidized bed dryers etc.).

3.3 Calcination

In the gypsum industry calcination is the thermal processing of gypsum to change the hydration state of its dihydrate content (calcium sulphate dihydrate, $CaSO_4.2H_2O$) by partly or completely removing its chemically bound (i.e. crystal) water in order to produce hemihydrate ($CaSO_4.1/2H_2O$) or anhydrite ($CaSO_4$) respectively. It is a reversible process that can be repeated almost indefinitely, which is why gypsum has been characterized as "eternally" recyclable. Specifically, when the calcined (i.e. dehydrated) material is mixed with water it rehydrates into its original state and sets, obtaining a relatively high strength by forming a crystalline structure.

Four different basic plaster products are commercially produced by calcination of gypsum, depending on the method and chosen conditions (temperature, pressure, rapidity); α- and β-hemihydrate, soluble anhydrite and insoluble anhydrite, also commonly called "dead burnt gypsum". All types are called "stucco" in the industry and the hemihydrates are also commonly known as "plaster of Paris".

The anhydrite types are produced at higher calcining temperatures from ~180^{o}C and up to 540^{o}C. Soluble anhydrite readily rehydrates in contact with water to the dihydrate state and sets very rapidly [2], and its uses in technical applications are limited. Dead-burnt gypsum shows no setting properties and is mainly used in cement manufacturing [2,7].

α- and β-hemihydrate are formed in different calcination conditions and differ in their physical properties. α-hemihydrate is less reactive compared to the β-type, but its crystals are more prismatic and form a much stronger, denser and harder superstructure when mixed with water, which makes it advantageous for certain uses [5,7]. α-type plaster is produced in autoclaves under pressure and is mainly used in industrial plaster formulations with special requirements for its high mechanical strength [1,5].

In the manufacture of plasterboards calcination refers to the production of β-hemihydrate, whose crystals have a micro-porous structure and high specific surface. The produced stucco is more soluble than the α-type and when it sets after rehydration it has high porosity, but low mechanical properties and is therefore mainly used in lightweight building applications such as plasterboard or moulds [5].

3.3.1 Process Chemistry

Stucco for plasterboard manufacturing is produced by the Beta Process of calcination that results in the formation of β-hemihydrate. The ground gypsum feedstock is heated under regular ambient pressure at the temperature range of 120 to 165°C and the contained calcium sulphate dihydrate releases 75% of its crystal water as steam and converts to hemihydrate according to the equation:

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

Continuous controlled stirring of the gypsum mass inside the calciner is necessary to prevent localized overheating. Above the optimum temperature range unwanted side reactions involving excessive water loss occur, leading to the complete dehydration of gypsum into anhydrites.

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 gypsum is a mixture of calcium sulphate in varying states of dehydration ranging from uncalcined dihydrate to anhydrous forms [1,6,7]. The occurrence of the undesirable phases (i.e. that have a negative effect on the intended properties of stucco) and their varying amount are minimized by carefully controlling the parameters of the calcining process (temperature, pressure, heating method and rate, gypsum particle size etc.).

3.3.2 Calcination Equipment

3.3.2.1 Kettle Calciners

The kettle (Figure 3-4) is the most widely used calcination unit, available in several designs. In its basic form it is a cylindrical steel vessel with a height greater than its diameter enclosed in a refractory shell. The ground gypsum is indirectly heated by hot combustion gas introduced from a firebox below the vessel, which flows upwards around the kettle’s content and through horizontal flues for improved heat transfer. Gypsum is stirred by a vertical rotating agitator shaft with rabble arms.

Kettles can be operated in batch or continuous mode, depending on the desirable properties and applications of the produced stucco. In plasterboard manufacturing predominantly continuous kettles are used. Ground gypsum is fed from the top of the kettle at a constant rate and the calcined stucco is discharged, typically at 130 to 160°C, in a “hot pit” or product bin to cool rapidly and prevent any unwanted further calcination, either through a side overflow pipe or a plunging tube at the lower section of the kettle depending on the unit’s design [6,7]. The chemically bound water released during calcination is removed through a steam vent at the top.

A modern variant type of continuous kettle is the submerged combustion kettle in which the process takes place inside the vessel’s shell by discharging the combustion gases through a tube directly into the calcining mass. These kettles are more efficient from the standpoint of energy consumption but result in a more violent calcination [7], thus requiring accurate temperature control to avoid undesirable overheating effects.

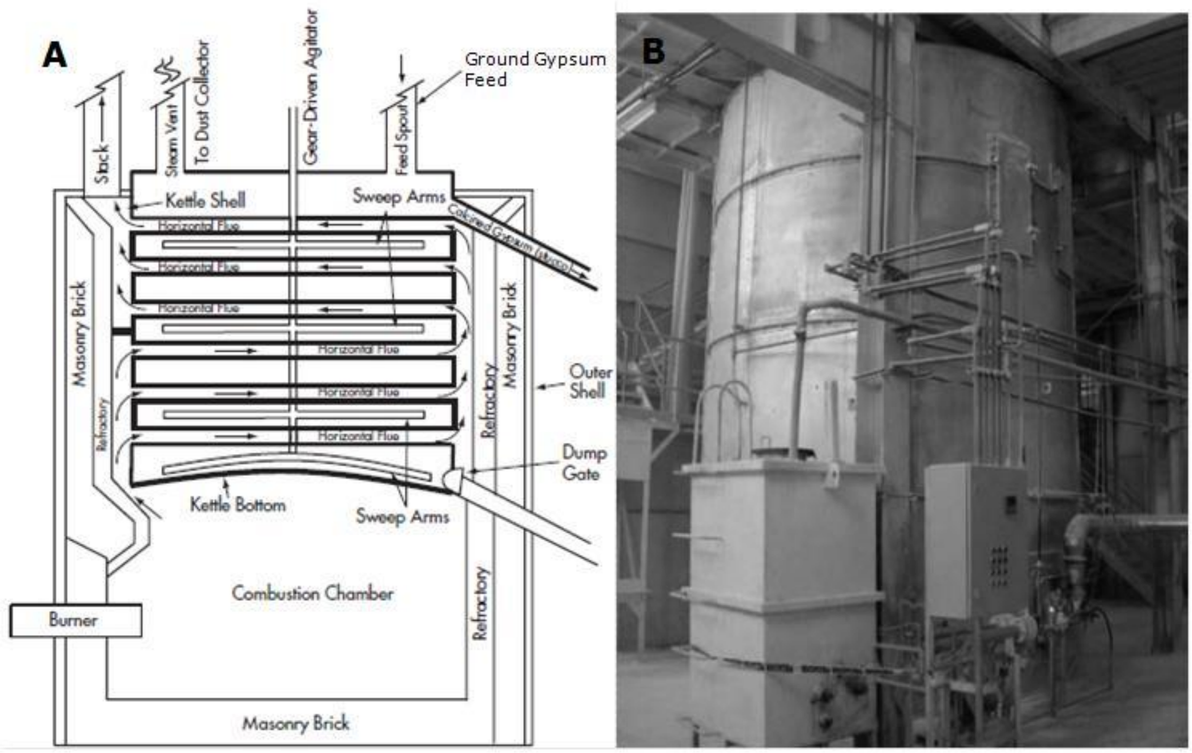

Figure 3-4 General sections (A) and exterior view (B) of a gypsum kettle [7]

3.3.2.2 Rotary Kilns

Coarse gypsum up to 50-60 mm in diameter can be calcined in directly heated rotary kilns. The feed is introduced from the top of the kiln and travels across it while it is calcined in direct contact with hot combustion gases from a burner. The stucco is discharged from the bottom at the end of the kiln and the gases exit from the top and pass through a separator (i.e. cyclone and/or filter) for recovery of the entrained finer gypsum particles. Rotary kilns can be either co-current (Figure 3-5) or counter-current.

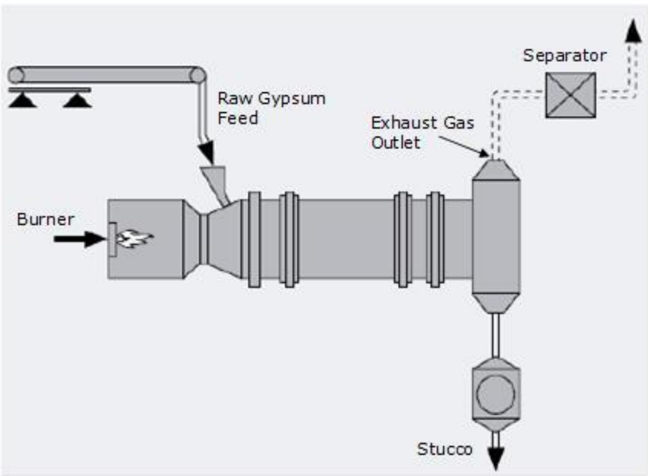

Figure 3-5 Layout of a co-current rotary kiln for gypsum calcination

Rotary kilns are the second most commonly used type of gypsum calciner for β-hemihydrate production, but in plasterboard manufacturing they have been largely replaced by continuous kettles or by more modern single-unit grinding and calcining equipment. They are however still used in the gypsum industry, especially for construction plasters [7].

3.3.2.3 Single-unit Grinding and Calcining Equipment

An increasingly popular option in plasterboard manufacturing plants is heated calcination mills in which the raw feed is dried, ground and calcined to stucco in a single stage. These modern mills can readily process gypsum rock of diameter up to 60 mm, as well as mixtures of natural gypsum, FGD and recycled gypsum.

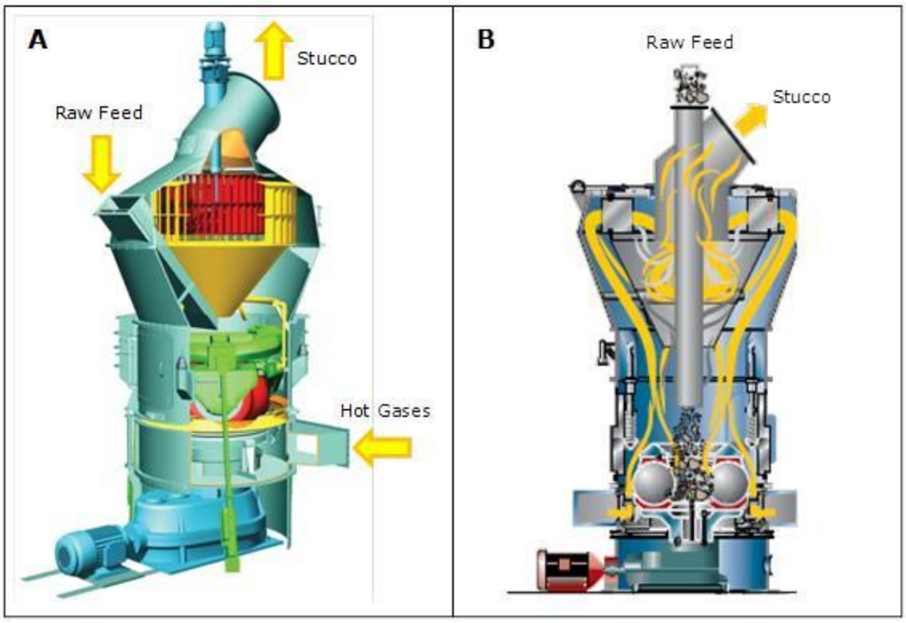

Figure 3-6 Example types of heated calcination mills; Gebr. Pfeiffer vertical roller mill (A), Claudius Peters ring-ball mill (B)

Drying and calcination of gypsum takes place by direct contact with hot gases in conjunction with fine grinding and classification, thus eliminating the need for individual rotary driers, roller mills and calciner units and resulting in higher energy efficiency. The produced stucco exits entrained in the gas and it is separated in downstream separator units. Depending on the design, the specifications and the range of desired product characteristics and properties, air-swept heated mill types include vertical roller mills, ring-ball mills, impact mills etc.

3.3.3 Stucco Production Process Flow

Stucco production is the first step of the plasterboard manufacturing process and includes all raw material pre-processing stages and calcination. Depending on the feedstock mix and the equipment used in each plant, which are both interlinked and directly related to the know-how and to the special quality characteristics and specifications of each company's product, there are differentiations to the overall process set-up.

More specifically, the gypsum input in a plasterboard plant can consist of only natural or FGD gypsum or a mixture of both, also including a part of recycled gypsum. The fine-grained FGD gypsum does not need to undergo crushing and grinding, but due to its high free moisture content it usually must be pre-dried prior to calcination, whereas natural gypsum is firstly crushed and ground to appropriate grain size, potentially with simultaneous pre-drying, and subsequently calcined, or alternatively it is fed straight to a calcination unit where it is conjunctively ground and dried.

The handling of recycled gypsum depends on its quality characteristics when delivered to the plant. Usually plants that rely exclusively on FGD have more strict requirements regarding recycled gypsum's particle size, while the ones that use natural gypsum accept recycled material in coarser form, so that it can be processed along with conventional feedstock. Naturally, when a feedstock mix of natural, FGD and/or recycled gypsum is used, each raw material is introduced in the process at the opportune point. Some indicative flowsheets are shown in Figure 3-7.

Gypsum and stucco are usually transferred from one stage to another by means of screw conveyors or bucket elevators. Stucco is intermediately stored in large silos for its subsequent use in the board line.

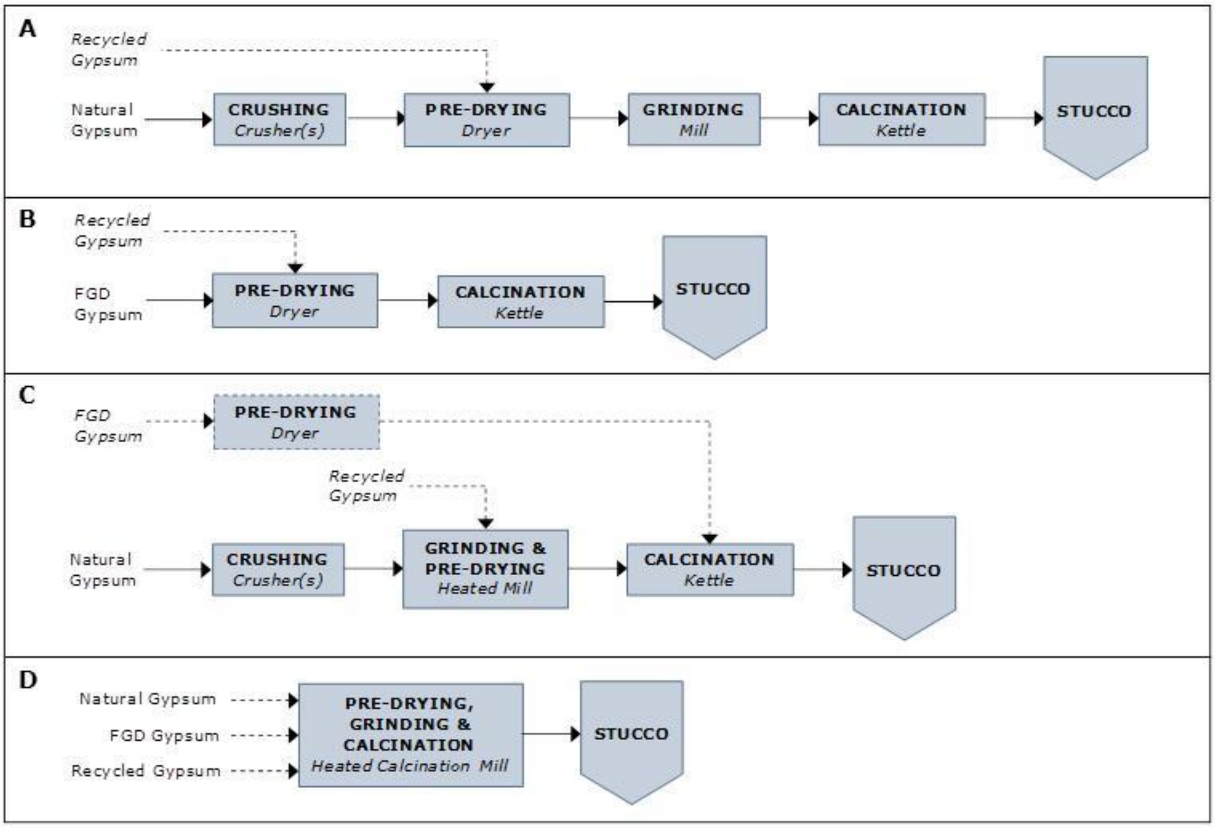

Figure 3-7 Indicative process flowsheets for stucco production

3.4 Plasterboard Production

Gypsum plasterboards are produced on large highly automated board lines in a continuous operation shown in Figure 3-8. The main sections are analyzed below.

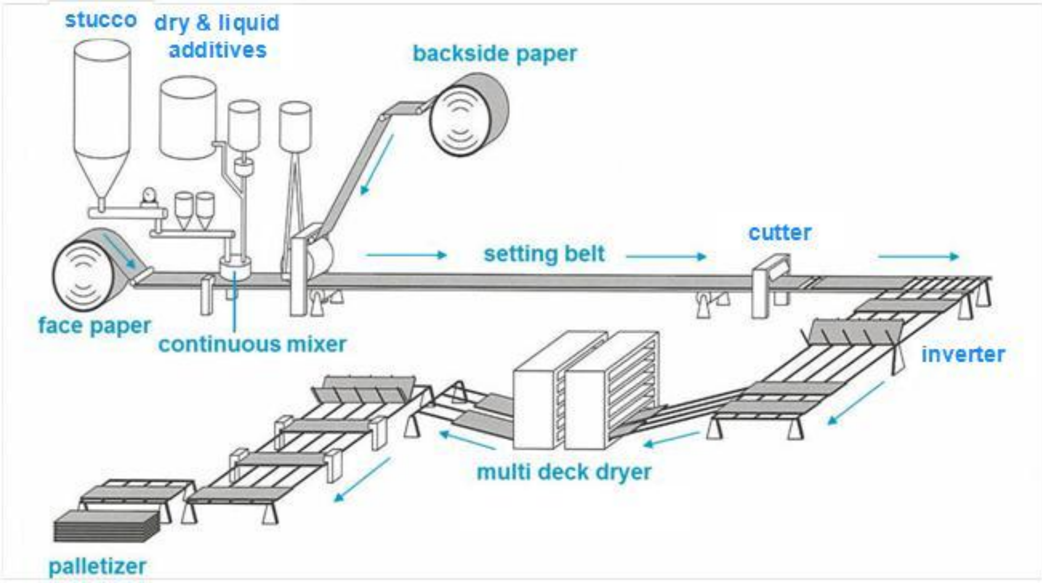

Figure 3-8 Plasterboard production line

3.4.1 Blending of the Stucco Slurry

The slurry that comprises the board's plaster core is produced by mixing stucco with water and appropriate dry and liquid additives and admixtures in defined amounts according to the so-called "recipe" followed in each plant.

Stucco is accurately metered and blended with the dry additives mix in a mixing screw conveyor and the dry ingredients are fed to a continuous mixer where water with premixed liquid additives is added. The resulting slurry is deposited on the bottom sheet of paper at the forming station.

To achieve proper consistency and fluidity of the slurry and to ensure complete rehydration of stucco back to gypsum, the added water is in excess of the stoichiometrically required amount for the rehydration reaction. This excess water is later driven off by drying the boards.

The specific recipe and most importantly the types and quantities of additives used determine the particular properties of the board and therefore depend on the type of plasterboard produced. Generally, stucco makes up for at least 95% of the material used prior to mixing with water, and additives include at least starch, fibres and an accelerator, among others [7]. Table 3-1 shows some commonly used additives in plasterboard production and their respective attributes. However, it should be noted that exact recipes are essentially technical and commercial exclusivities of each manufacturing company.

Table 3-1 Common additives used in plasterboard manufacturing [2,5,6,7,8]

Additive	Attribute
Starch	Helps the paper facings adhere to the plaster core and protects the physical bond between the gypsum crystals and the paper during drying
Paper pulp / Shredded paper	Increase the core's tensile strength and the impact resistance of the board
Glass fibres	Increase the board's strength and resistance and add elasticity and fire-resistance properties
Finely ground gypsum	Provides more sites at which gypsum crystals can grow, thus accelerating the setting rate
Potassium / Copper / Ammonium Sulphate	Cause the gypsum to precipitate quicker and accelerate the setting rate
Detergent	Foaming agent that entrains air into the core material resulting in a less dense plaster, which makes the board lightweight
Lignosulphonates	Improve the flow of the slurry so that less water is required
Fluidizers / Dispersants	Allow better wetting and mixing of components in the mixer at lower water level, thus decreasing water demand, improve the dispensation of the slurry and protect the board edges from shrinking during drying.
Dextrose	Improves paper bond at the ends of the boards
Asphalt and wax emulsions	Add moisture resistance properties
Vermiculite	Adds fire-resistance properties

3.4.2 Board Forming Station

At the forming station the paper is unrolled on racks that run below and above the mixer so that the stucco slurry can be "sandwiched" in between. The slurry from the mixer is poured on the bottom sheet of paper moving on a conveyor belt and covered with the top sheet. Two small mixers may be used to deposit slurry of higher density along the board's edges in order to improve their strength and facilitate handling [6]. The roughly formed board passes between edge guides and moves on under a roller or a forming plate to obtain the specified thickness. Finally an adhesive is added to seal the paper along the edges. It should be noted that the bond between the paper and the board's plaster core is achieved by the growth of gypsum crystals into the fibrous pores of the paper during setting and not by the use of adhesives.

The paper used in plasterboard manufacturing, called facing or lining paper or plasterboard liner, is a special multi-ply couched cardboard, typically recycled, and gives the board most of its tensile strength. The face of the board is usually ivory-coloured and the back side gray.

3.4.3 Setting and Cutting

After it is formed, the long continuous sheet of plasterboard travels along on a conveyor belt of about 100 m to several hundred meters length, while setting. The length of the board line is designed in conjunction with the belt's speed and capacity to allow the required time for the plaster core to set. Setting time usually varies between 0,5 and 5 min. The speed of the line depends on the design of the machine and the type and thickness of the board manufactured, but it usually ranges between 0,5 and 3,0 m/sec, a typical line speed being around 1 m/s [2,7].

The actual setting process refers to the completion of the rehydration reaction of the hemihydrate contained in the stucco which converts it back into interlocking dihydrate crystals. The basic reaction is the reverse of calcination, but the newly formed dihydrate is more solid and stiff than the one originally calcined:

$$CaSO_4.1/2H_2O + 3/2H_2O \rightarrow CaSO4.2H_2O$$

Due to the above reaction the core of the plasterboard sets and bonds to the paper facing, and hardens enough so that the board can be cut by the time it approaches the end of the line. At that point an automatic cutter cuts the continuous board at specific intervals to produce individual uniform panels of the proper length. As they continue to move, the boards pass by an inspection point where out-of-specification boards (i.e. wet rejects) are diverted from the process and the rest are turned over and proceed to the dryer.

3.4.4 Drying and Finishing Process

At their final production stage, the boards stacked in layers slowly enter a continuous multi-deck drying kiln where the excess free moisture (i.e. the excess water added at mixing) is evaporated. This is accomplished by direct heat transfer with hot air streams, while the boards move through three or more drying sections (zones) depending on the kiln/process design, where they are exposed to gradually decreasing levels of heat. Drying time ranges between 35-60 minutes and the boards exit with less than 0,5% residual free moisture. The temperature and humidity are closely controlled during the drying process to prevent re-calcination of the gypsum core.

At the exit of the dryer the boards are once more inspected and off-specs (dry rejects) are removed. The finished plasterboards are conveyed to a machine that trims their ends to produce accurate lengths and then are bundled in two, stacked and taken to storage.

3.5 Energy Use and Efficiency

Plasterboards are among the most environmentally friendly construction products due to four main reasons; the long established use of recycled lining paper, the large substitution of natural gypsum resources with synthetic FGD, the essentially 100% recycling of plasterboard waste arising from production and the increasing incorporation of post-consumer recycled gypsum in the manufacturing process. Furthermore, plasterboards have very low embodied energy based on cradle-to-gate values.

Plasterboard manufacturing is nonetheless quite energy intensive, particularly regarding the calcining and board drying operations. The plasterboard dryer consumes more energy than all the other stages of the process combined, while calcination represents the second most energy-intensive stage, followed by the drying and grinding of gypsum raw materials [6]. Previous estimates on the total energy required per square meter of standard 12,5 mm thickness board range between 23,6-28,4 MJ [2,6,7].

The use of natural gas for covering thermal energy demands is widespread. Calcination and drying processes are entirely fueled with natural gas in the largest part of the industry, as the use of coal, oil and LPG is being increasingly abandoned. In addition to the financial and environmental benefits of natural gas, this shift was also prompted by the use of directly fired drying equipment, in which clean-burning fuels are highly preferable to prevent contamination of the raw materials and/or of the plasterboard product [7]. The supplementary use of alternative fuel (e.g. waste fuel) is not uncommon, especially in calcination, however fuel flexibility is considered limited within such product quality related restraints.

The use of alternative energy sources has not been generally favoured despite the gypsum industry's efforts to introduce them in the energy mix, due to availability issues, technological impediments and cost considerations.

However, in the last 50 years major strides have been made to reduce energy consumption and improve energy efficiency, which have led the industry close to the theoretical optimum energy consumption value. The rise in energy costs over time encouraged the investigation and development of process technology to reach lower energy requirements. The most important advancements include the shift from batch to continuous kettles, the submerged combustion kettles that offer higher energy efficiency than indirectly heated units and the gradual replacement of rotary kilns with kettles of improved design.

Heated mills and directly fired grinding/calcination units rendered the stucco production process more "compact" and continuous innovation in calcination technologies and equipment further improved its energy efficiency. New cutting-edge technologies allow higher hot gas inlet temperatures and lower gas volumes in direct heat transfer systems that lead to optimal energy consumption and offer a more accurate temperature control regime.

The minimization of the water/stucco ratio in the slurry by using more "sophisticated" additives decreased considerably the plasterboard drying energy demands. Extensively implemented energy-saving practices also include judicious fuel selection and use and insulation measures.

The remaining gap between theoretical barrier and current thermal energy use levels is mainly due to heat losses, however latest generation heat recovery systems are increasingly being adopted. Heat recovery systems allow considerable energy savings by preheating air streams needed in several stages of the process with collected heat from calciners' and dryers' flue gas recirculation, thus achieving to recapture a large part of the conditioned temperatures that would otherwise be lost. Dryers and calciners of latest technology have integrated such systems, but these can also be added on the existing units.

Regarding electrical energy, consumption has also approached the feasible minimum due to the widespread adoption of variable speed drive technologies that regulate power input, thus avoiding over-consumption of electricity. Variable speed drive systems match the speed of motor-driven equipment to the process requirements and lead to significant electrical energy savings.

Based on the above there is no scope for further reduction of energy consumption and improvements in energy efficiency in the plasterboard manufacturing industry.

Most major EU plasterboard manufacturing plants have both heat recovery and variable speed drive systems installed and perform energy audits; hence there is little room for low or medium cost energy saving measures, as long as "house tiding" practices are implemented as requested by energy audits. High capital cost measures such as upgrades in new calcination/drying equipment or energy production technologies could have some positive impact, but, given that plaster is a commodity facing a fall in demand and an increasing pressure on prices, the adverse market situation in Europe and the decreased share of European production in the global picture hinder short term investments in this direction.

Taking into account the increasing energy prices, this leaves fuel flexibility (i.e. the use of different fuels according to price and availability) as perhaps the only energy saving and overall cost reduction issue in plasterboard manufacturing, although within the restraints of ensuring product quality.

3.6 Process Waste Streams and Atmospheric Emissions

3.6.1 Atmospheric Emissions

Plasterboard manufacturing is generally considered a “clean” industry.

Crushing, grinding and handling of gypsum raw materials and stucco at the plant, including the calcination step of the process, the blending of dry raw materials for plasterboard production, as well as the final trimming of the finished board result in dust emissions, which are minimized by particulate emission control systems. High efficiency baghouses and/or electrostatic precipitators are installed and used in all modern plasterboard manufacturing plants.

Fuel combustion for covering the process’ thermal energy demands results in the common atmospheric emissions (CO_2, CO, SO_2, NO_x, CH_4 and VOCs) as in any process where fuels are used. Both gypsum calcination and plasterboard drying process require relatively low temperatures where no significant NO_x is generated [6]. Moreover, the extensive switch from heavy fuels to natural gas has practically eliminated SO_2 emissions and the use of high combustion efficiency burners, as well as the whole set of energy efficiency widely adopted measures have minimized the release of all other pollutants.

Regarding CO_2, the process involves only fuel CO_2 generation (i.e. there is no chemical release of CO_2). As a consequence of continuous process innovation that led to energy efficiency improvements and significant overall reduction in energy consumption over the last 50 years, both direct and indirect carbon emissions of the plasterboard industry have been minimized close to the theoretical benchmark. In fact, fuel CO_2 emissions have proportionally decreased more than the respective reduction of thermal energy consumption thanks to the shift to natural gas.

3.6.2 Liquid Waste

The plasterboard manufacturing process itself generates hardly any liquid effluents. Liquid waste that may be generated during production, e.g. due to poor slurry quality at forming stage, is internally recycled. However some liquid waste are indirectly generated from plasterboard plants from the washing of equipment and spaces and the rainwater that washes away gypsum dust from yards and open storage areas. These runoff waters are typically drained and filtered or drawn into containment areas and the resulting sludge after settling is disposed to landfills [6].

3.6.3 Solid Waste

A small amount of plasterboard waste is generated from the manufacturing process as wet and dry out-of-specification boards. Some solid waste also is also produced during the final trimming of the boards. As already noted, 100% of production waste is recycled, at least as far as standard plasterboards of Type A are concerned. However, some special technical boards are currently considered unfit for recycling and they are disposed to landfill, although the quantities generated are relatively low.

4. Key Manufacturing Parameters Affected by the Use of Recycled Gypsum

The origin, type and properties of the raw materials are major determinant factors of the technical characteristics of a production process, which is adapted accordingly in order to efficiently achieve the desirable product quality. In this context, the key parameters of the plasterboard manufacturing process that are affected by the use of recycled gypsum can be grouped into two main categories based on the scope of respective impact; feedstock quality and technical process features. Essentially these are closely interlinked and co-dependent. The introduction or increase of recycled gypsum usage in the process alters the composition and quality related characteristics and properties of the so far standard used feedstock/feedstock mix and this in turn has an effect on technical issues of production that call for process modifications in order to minimize and/or eliminate negative implications on product quality, as well as on production costs.

In the sections that follow, the impact arising from the use of recycled gypsum and its particular properties on each of these parameters is analyzed in relation to their role and significance in the manufacturing process. It should be noted that the systematic high % usage of post-consumer recycled gypsum is a relatively new practice in the plasterboard industry and this fact reflects in the lack of extensive literature references on the potential effects on the manufacturing process. The information presented in this chapter is therefore mainly based on:

- feedback from the industrial partners of GtoG, obtained during the pilot plant visits carried out by NTUA in June 2014. This information reflects experience from regular/every-day practices.
- the experience gained from the 2nd production trials, as recorded in the questionnaires on re-incorporation issues (see section 2.2.3).

4.1 Feedstock Quality Related Parameters

4.1.1 Particle Size

Control of gypsum particle size is absolutely necessary in order to obtain the exact stucco properties required for plasterboard manufacturing.

Particle size is a determinant factor in order to achieve uniform heat transfer in the calciner, given its operating parameters, thus ensuring calcination efficiency, and it also relates to the excess water demand in the slurry mixer since it affects the viscosity of the stucco slurry.

In practice the particle size of recycled gypsum differs from both natural and FGD gypsum. As a result, the increased use of recycled material has an impact on the particle size distribution of the feedstock mix, which reflects on stucco quality.

When using natural gypsum, the recycled gypsum that is delivered as a finer powder may cause problems at the mixing stage, since the result of the milling operation depends on the feed size range in relation to the type and specifications of the grinding equipment available. When FGD is used, finer particle size of recycled gypsum is required to obtain a more uniform feedstock mix and limit the related undesirable effects, given that plants relying on FGD do not employ grinding equipment.

It is therefore clear that in order to minimize the impact on the process, the particle size of recycled gypsum should be compatible with that of the conventional feedstock already used.

4.1.2 Free Moisture

The free moisture content of raw materials affects the feed/stucco mass ratio; since the amount of dry feedstock of given purity needed to produce 1 tonne of stucco is specific, the feed/stucco ratio increases when wetter feed is used. Free moisture is also directly related to the energy consumption of feedstock drying operations prior (or simultaneously) to calcination; the more the moisture, the higher the fuel consumption and vice versa. Thus, the high moisture of a raw material reduces its value.

Apart from the inherent moisture of the raw materials, their moisture content also highly depends on the climate conditions during transportation and storage, the duration of storage prior to use and on the storage conditions (i.e. whether they are stored indoors or outdoors in covered areas).

The inherent moisture of recycled gypsum can vary widely, since it depends on the wet/dry production rejects ratio and the handling conditions at the jobsites where the post-consumer waste originates from.

When the % usage of recycled gypsum in the manufacturing process is low, the impact on the energy consumption due to the change of feedstock’s moisture content is negligible. However, if the recycled material has higher moisture content than the conventional feedstock used, its increased % incorporation considerably raises drying energy demands and results in higher fuel consumption. This is often encountered when natural gypsum is used as conventional feedstock. On the other hand, the use of recycled gypsum with lower moisture content can have small or even positive impact on energy consumption, especially when mixed with FGD which is a material of high inherent moisture. It is therefore evident that the effect of recycled gypsum’s moisture content on energy consumption and respective cost is a question of meeting the manufacturer’s standards.

Often, the amount of a certain feedstock component that a gypsum plant can blend in its mix is dictated by the thermal capacity of the available drying system. [9] The feasible maximum of % re-incorporation of recycled gypsum in the process may be thus limited by high free moisture. Also, high moisture gypsum has a greater tendency to stick and build up on conveying equipment. [9]

The mixing of wet with “drier” recycled gypsum batches is a common practice to reduce the feed’s moisture. The “wet-end” waste on the boardline is usually blended with dry waste (either internal or external) to prevent blockages and to control the calcination without excessive moisture content in the batch.

4.1.3 Purity

Purity is the % w/w $CaSO_4.2H_2O$ content of gypsum (on a dry basis) and constitutes the most important quality index of gypsum as a raw material. It also directly relates to the energy consumption of the calcination stage; due to the endothermic nature of the calcination reaction, the higher the purity the higher the thermal energy (i.e. fuel) demand, because feedstock contains more chemically bound water that has to be driven off. However, high purity of feedstock is preferable for product quality reasons, mainly because it results in the production of lower weight plasterboard [9].

Recycled gypsum's typically lower purity decreases the purity index of the feedstock mix and even though this results in lower energy consumption, producers are faced with product quality constraints. As the level of recycled gypsum incorporation increases, the negative impact could become considerable, especially for processes where high purity FGD gypsum is used as raw material.

If the purity of recycled gypsum is compatible with the conventional feedstock already used, any negative impact on stucco and plasterboard quality is minimized, while energy consumption is kept to standard levels.

4.1.4 Residual Paper and Fibre Content of Recycled Gypsum (TOC)

The residual paper contained in recycled gypsum originating from plasterboard waste is a major limiting factor of the threshold percentage for its re-incorporation in the manufacturing process.

The paper flakes affect the consistency of feedstock and may form agglomerations in the calcining gypsum mass. In indirectly heated calcination units paper pieces tend to stick to the walls of the vessel and form insulating layers or spots that hinder efficient heat transfer.

Regarding the plasterboard production step, excess paper content can cause mixer blockages during the formation of the stucco slurry and also increases water demand and, consequently, the energy demand during the drying process. High paper concentrations may also affect the fire rating and overall safety specification of the board.

Moreover, potential process effects are related not only to the amount of paper contained in recycled gypsum but also to the size of paper flakes. Naturally, larger paper pieces are more likely to cause equipment blockages (e.g. to sieves, mixers etc.) and impact production rate.

Historically in-plant plasterboard recycling facilities have low paper removal efficiency, since the re-incorporation of exclusively production recycled gypsum up until recently had inconsiderable impact on feedstock quality; due to the small amounts introduced the % paper content in the total mix remained negligible. In fact, basic production waste recycling lines often completely lack a paper removal stage. Nevertheless, many of these facilities became more and more involved in the processing of post-consumer waste, which results in recycled gypsum with higher paper content compared to the recycled material received from external gypsum recyclers.

The paper inclusion level in feedstock, as well as the acceptable size of paper pieces, may be specific process-dependent (i.e. existing sieving stages of raw materials and/or stucco, aperture sizes and capacity of available sieves, type of calcination equipment etc.), but in any case it has a maximum permissible value which determines the feasible level of recycled gypsum usage in plasterboard manufacturing in relation to its residual paper content. Hence, the paper content of the recycled material is a parameter of key importance.

Another predominant limiting factor of recycled gypsum's maximum usage is its paper and wood fibre content (cellulose fibre). Fibre is very difficult to remove entirely from recycled gypsum. Just like paper, fibres hinder efficient and uniform heat transfer during calcination and can also have a negative impact on production rate and render the process-economic.

The TOC (Total Organic Carbon) value of recycled gypsum is an index of its paper and fibre content.

4.1.5 Water Soluble Salts

Water soluble salts refer to chloride, magnesium, sodium and potassium salts. The presence of these salts in feedstock affects the paper bonding in plasterboard production; they readily dissolve when stucco is mixed with water and during the drying of the plasterboard the salts migrate to the paper – core interface and interrupt the bond [9]. The chloride content of feedstock is especially considered a very important parameter which also impacts the calcination rate of conversion. If recycled gypsum has high content of chloride and/or other water soluble salts, its increased use could therefore cause negative effects on the process.

It should be noted that water soluble salts are common impurities in conventional gypsum, both natural and synthetic [9], and hence, their presence in feedstock is not particularly linked with the use of recycled material. Nonetheless, a potential relatively higher salt content in recycled gypsum could be related to residual paper. In any case, since they are one of the most important parameters affecting the physical properties of plasterboard, related specifications for the water soluble salts content of recycled gypsum are required.

4.1.6 Silicone Content of Recycled Gypsum

The presence of silicones in recycled gypsum is due to the additives contained in the plasterboard core, to the glue used for the board's edges and to certain impurities related to its post-consumer origin (e.g. ceramic tiles). In case special technical boards (e.g. water-resistant plasterboard waste) are included in the recycling process the produced recycled material can have relatively high silicone content [10]. Silicones are hydrophobic and act as water-repellant agents in stucco; they thus negatively affect the excess water amount required to form the fluid slurry and create higher thermal energy demand in the board dryer [9]. Moreover, they can cause variability in water absorbance and disruption of the board core structure generating blisters and blows [10]. Hence, the use of recycled gypsum with high silicone content affects the wetting process in the slurry mixer and the activity of the foaming agent, which eventually has a direct impact on the cost and the quality of the board.

The silicone content of recycled gypsum is considered an important parameter by plasterboard manufacturers and it has to be monitored and kept under a low threshold value to avoid negative impact on the process. In this scope, a related specification should be established. X-Ray diffraction (XRD) is used to identify whether the SiO_2 present is of amorphous or crystalline nature. ASTM C-471M Standard Test Methods for Chemical Analysis of Gypsum and Gypsum Products – Section 10 describes a wet chemistry method to determine SiO_2 and insoluble matter [9].

4.1.7 Other Impurities in Recycled Gypsum

Other impurities that may be present in recycled gypsum due to the origin of (part of) the material from demolition / deconstruction activities can be distinguished between visible coarse impurities like metal objects (such as screws, nails etc.), wood, ceramic tiles, plastics etc. and trace elements like heavy metals, organics and asbestos. The types and amounts of impurities may vary depending on the waste sources and process effects arising from impurities present in feedstock due to the incorporation of recycled gypsum may differ considerably in nature, in their stage of occurrence, as well as in importance.

In any case, when delivered at the plant recycled gypsum should be free of all physical contamination and have low content of chemical impurities in order to avoid any considerable impact on the process and the contamination of the finished products.

Specifications with limit values for trace elements, mainly heavy metals, are considered necessary for recycled gypsum to prevent any human or eco-toxicological impacts. Special attention must be given to the absolute absence of asbestos, which is an unconditional criterion for acceptance of recycled gypsum at the plant and related test results should accompany every batch delivered.

4.1.8 Feedstock pH

pH is a general quality index of relative acidity/alkalinity of the material and relates to the quality of the final plasterboard product where acidity is problematic and, thus, unwanted. Recycled gypsum's pH naturally affects the respective value of the new feedstock mix, but it is not considered a highly important parameter as long as it is not acidic; a value within the range of the normal pH (neutral or slightly alkaline) of natural gypsum is preferable.

4.2 Technical Process Related Parameters

4.2.1 Storage

Proper storage of raw materials in indoor spaces contributes to moisture content control and minimizes the risk of any external contamination.

Recycled gypsum requires sufficient storage space to ensure production continuity and to achieve a certain level of homogeneity between loads with fluctuating characteristics. As a consequence of its increased usage, manufacturers have to designate new spaces in their existing storage facilities or invest in alternatives. Separate storage for "quarantined" recycled gypsum stock intended for return is necessary in order to eliminate the risk of accidental inclusion of unfit material into the process.

4.2.2 Raw Material Feeding

Plasterboard manufacturers may have to re-design their raw material feeding system. The introduction of higher percentages of recycled gypsum in feedstock will cause the need for speed adjustment or up-scaling of the mechanical feeding equipment (typically conveyors). Technical limitations in the existing devices (e.g. conveyor motors, size, capacity etc.) might even constitute restricting factors for further recycled material incorporation, given that “hardware” modifications and replacements will not be preferred due to cost reasons.

4.2.3 Process Conditions

Conditions control mainly refers to temperatures during the calcination and drying stages.

Regarding calcination, the aim is to maintain stable stucco production of consistent quality in order to ensure plasterboard quality, as well as production rate. As already noted, the strict control of calcination temperatures minimizes the occurrence of unwanted phases in stucco (i.e. unreacted dihydrate and completely calcined anhydrite). Set points primarily involve gas stream and equipment operating temperatures and are determined based on the feedstock properties (mainly purity, chemical composition and particle size) and the technical design and operation specifications of the available equipment units.

The impact of recycled gypsum on feedstock quality may therefore call for adjustments either in the very set points or, most likely, in other related process conditions such as hot gas and incoming material volumes, after testing and assessment of the available options.

In a respective manner, the impact of recycled gypsum use on water demand in the stucco slurry (see section 4.2.5 below) may call for temperature adjustments in the complex multi-zone heat transfer system of the plasterboard dryer kiln.

This type of process modifications may have negative effect on fuel consumption.

4.2.4 Slurry Dosage

The recipe of the slurry has to be adjusted according to the quality of the produced stucco (particle size and phase composition, i.e. % content of dihydrate and anhydrite), which directly depends on feedstock characteristics. Despite the adjustments in set points that may be made at the calcination stage of the process, the quality of stucco after the increased recycled gypsum reincorporation may be inevitably affected up to a certain level. Hence, the amounts and possibly the types of additives are likely to be modified so that the slurry quality is restored to the standard levels, while retaining the appropriate amount of stucco in the dosage so that production rate remains stable.

4.2.5 Water Demand

The water/stucco ratio at the slurry mixing stage depends before all on raw material nature (purity and particle size) which is in turn a determinant factor of stucco quality. A theoretical limit applies only to the stoichiometrically required amount of rehydration water in order to convert the hemihydrate and anhydrite phases present in stucco into dihydrate. In practice, however, the optimum water/stucco ratio includes a considerable volume of excess water so that the slurry obtains proper fluidity.

Water demand directly relates to the energy consumption of the subsequent plasterboard drying stage; the higher the water/stucco ratio the more the thermal energy needed to evaporate the excess water off. The use of dispersants and fluidizers added to the stucco slurry allows better wetting and mixing of components in the mixer at lower water level, but increases process costs.

The changes in feedstock and stucco properties caused by the high incorporation of recycled gypsum are therefore likely to affect the water demand of the plasterboard production process. Effects on feedstock's purity will have a clear impact on the stoichiometric water requirement, whereas changes in particle size distribution may affect the viscosity of the stucco slurry. Hence, a possible increase in water demand will result in higher fuel consumption in the plasterboard dryer kiln. On the other hand, the excess water amount can be kept at standard levels by changing the recipe (e.g. by using more liquefier additive). Since both these options lead to higher costs, the optimum solution will have to be investigated.

4.2.6 Setting Time

The setting behaviour of the board's plaster core as well as the length and speed of the setting belt are inter-related. Moreover, setting can be initiated and/or accelerated by special additives.

The changes in the slurry's setting time arising from the use of recycled gypsum can be addressed by adjustment of the board line's speed (given its existing available length) to the level that this is feasible with the available equipment/board line design. Possible technical impediments may call for further adjustments to regulate the setting time itself by appropriate changes in recipe; the amounts of additives and the composition of the additives' mix can be modified to amortize the impact on setting time and restore it to standard levels. Such measures may also serve to mitigate negative effects on electrical energy consumption and respective cost resulting from the line's speed modifications.

In all, the optimum solution has to be a combination and coordination of line and recipe adjustments through investigation and assessment of the comparative effect on total cost, while ensuring final product quality.

4.2.7 Variable Manufacturing Costs

Recycled gypsum is obtained from recyclers in lower prices than conventional gypsum and this has positive impact on production costs. However the net combined effect with the other cost fluctuations caused by the way its use directly or indirectly affects individual process parameters (fuel and electrical energy, water demand, recipe changes, production rate etc.) has to be investigated.

In the previous sections there are references on the multiple impact of recycled gypsum use on thermal energy consumption in relation to several feedstock and process related parameters and again the net overall effect has to be assessed.

Possible changes in the bulk density of the feedstock mix and of the blended gypsum slurry and board line speed modifications are the main factors of impact on electrical energy consumption of the mechanical conveying equipment.

Calcination throughput may be affected by changes in raw materials' purity and/or moisture content (i.e. changes in the feed/stucco ratio). This, as well as line speed changes, may impact production rate and the cost per unit of product.

The potential impact of recycled gypsum use on stoichiometric water demand is considered less important from a financial point of view, because it reflects only in water cost (a variable of relatively low economic significance), as opposed to the impact on excess water that also relates to drying fuel requirements and to the use of additives and their respective costs.

The impact on variable manufacturing costs is the object of study of the energy & techno-economic analysis carried out in the framework of Sub-action B3.2 of GtoG project and is presented in detail in Chapter 6 with special focus on energy consumption.

4.3 Experience Gained from the Production Trials

4.3.1 1st Round of Trials – "Business as Usual"

The key conclusion drawn from ground observations and experiences gathered from the normal everyday practices of each plant based on the information obtained during the pilot plant visits in June 2014 (i.e. after the completion of the 1st round of production trials) is that currently, plasterboard manufacturers address recycled gypsum quality variations on a case-to-case basis. They have a "rough" knowledge of the quality of the recycled material they expect to receive from a recycler and overcome property fluctuations by adjusting the percentage of natural and/or FGD gypsum in their feed material mix and by modifying calcination and drying parameters, if needed, to reach the necessary stucco quality, which is generally used for plasterboard quality control. This "non-standardized" approach restricts the continuous and systematic inclusion of higher percentages of recycled gypsum in the daily production practices.

On the other hand, quality variations can also occur in conventional feedstock and the adjustments made to compensate them are usual challenges and part of a plant's daily production routine. In this context, so far experience has shown that at relatively low recycling levels the process effects may be tolerated and/or easily overcome.

4.3.2 2nd Round of Trials – Maximization of Recycled Gypsum Use

The contents of this section are based on the consolidated answers of the 5 manufacturers – partners of GtoG in the questionnaires on re-incorporation issues based on the 2nd round of trials. It should be noted that the points summarized below in most cases do not apply for all the 5 manufacturers that took part in the study; there were many individual references of re-incorporation problems encountered, restrictions and suggestions which relate to the process-specific differentiations among the pilot plants. However, these should not be considered less important, since the sample of plants comprises the largest and most advanced stakeholders of the sector.

Although high recycling rates were achieved –in any case significantly higher compared to the 1st round of trials–, the inclusion of recycled gypsum up to the 30% target was not realized in all five plants due to problems encountered in the process. Specifically, three out of five manufacturers commented on paper problems, all of them reported equipment shortcomings, two out of five reported moisture issues and one commented on the recycled material's purity. The complete list of problems and difficulties reported in the questionnaires, which may vary among the plants studied and are not applicable to all five cases, are summarized below:

- Physical limitations on storage space and management of recycled material; limited available spaces for the separate storage of accepted and off-spec material intended for return.
- Overflows and restrictions due to limited capacity (volume and/or motor power and speed restrictions) of the available conveyor belts for the feeding and transferring of recycled material.
- Problems related to the paper content of recycled gypsum and the size of residual paper pieces; sieve blockages during feed or stucco sieving causing delays, fractions of paper resulting in some bubbles or lumps in the plaster or lack of bonding between core and liners in plasterboards.
- Problems in the dosing units of stucco containing high percentage of recycled material due to caused decrease in stucco density.
- Problems in the drying of plasterboard; the specification/behavior of plasterboards with high content of recycling was changed causing boards to overdry.
- Limited technical detection capability of non-visible contaminants in recycled gypsum, such as fibres (mainly asbestos), chemical contaminants and hazardous materials; delays due to the long time needed for processing the analyses results, need for fast test methods where each load has a certificate of guarantee.

Regarding the quality of recycled gypsum, purity, particle size distribution, moisture and paper content constitute determinant factors of the maximum percentage of incorporation in some of the plants. In one case the recycled material received was out of the specifications of the plant and had to be pre-processed internally. On the other hand, one manufacturer reported that the specific material received for the trial was particularly clean, with low paper content and its quality was considered ideal and not representative of the recycled gypsum received on standard basis.

The process adaptations made during the trials in order to achieve the maximum re-incorporation include:

- Installation of extra weighing units for more precise monitoring of the recycled content.
- Changes in the speed of equipment; increase of the conveyor belt speed to its maximum in order to achieve sufficient feeding rate of recycled material, decrease of boardline speed in order to decrease stucco feed rate.
- Separate carrying out of the complete process step of stucco production with high content of recycling (separate dose of calcination, separate silos used, emptying and re-filling of total stucco system etc.)
- Recipe adjustments concerning the chemical additives used in the stucco slurry (e.g. adjustments in accelerator, foam and liquefier additives).

A list of equipment modifications that will be needed according to the manufacturers if the maximum reincorporation percentage becomes routine practice is given below:

- Upgrading of conveyor belts to greater capacity with enhanced motor power (wider and faster) for the feeding of recycled gypsum.
- Controls to vary the recycled content when supplying different parts of the factory flexibly.
- Rebuilding/enlargement of the complete actual pre-processing system for recycled gypsum (i.e. milling, drying, sieving, storage). Incorporation of a gas burner for drying the recycled gypsum powder, usually in a mill, prior to blending that will allow more effective blending with conventional gypsum and fine grade milling of recycled gypsum with very high levels of paper removal (e.g. in a pin mill).
- Inline moisture testing along the recycled gypsum feeding belt prior to blending with conventional feedstock.
- Rebuilding/enlargement of the complete transfer and dosage systems within calcination.

With regard to potential re-incorporation issues for the production of plaster, the manufacturers state that bonding compounds require very high quality levels of gypsum and thus, recycled gypsum quality parameters must align as much as possible with those of conventional feedstock in order to enable its inclusion in the process. This requires that impurities like paper, glass fibre, silicon oil, wood fibre are fully removed.

Concerning potential re-incorporation issues for plasterboard production the manufacturers report that since the quality of the feedstock mix will of course change with the increased recycling content, the whole process (recycling system, calcination, storage, dosage, recipes, drying system) needs to be adjusted accordingly, aiming at the same time at averting cost increases in energy, additional chemicals, due to speed reduction etc. Hence, they highlight the importance of a constant supply of recycled material of consistent high quality, compliant with the supply chain specifications, in order to ensure process stability and avoid board quality changes. In this context, variations occurring in the supply quality and standards of recycled gypsum (e.g. purity, differences in particle grading, excessive moisture, high paper content etc.) that lead to process implications such as facing paper and gypsum core bonding issues, excess gas use, poor material blending, strength and flexibility issues, inability to control the slurry recipe, multiple resultant failures etc. should be limited as much as possible.

Purity is specifically reported by one manufacturer as a major restriction with regards to increasing the level of recycling to higher percentages. The presence of silicone in the material is considered to pose a significant risk in its inclusion in the process and the moisture content is also pinpointed as of particular importance in relation to the potential occurrence of mold during handling of the recycled gypsum stock.

Moreover, it is considered that the current quality of recycled gypsum makes it unsuitable for use in the manufacturing of more technical products (i.e. apart from standard plasterboard) where increased purity is required and that since the trials were performed only on this one board type, the outcome cannot be conclusive in this respect. It is stated that the monitoring program for paper content and concentration of other impurities (e.g. silicon oil, wood fibre) in recycled gypsum should be strengthened in order to expand/generalize its high percentage of use in the plasterboard products range.

Finally, it is suggested that more tests are needed in order to enrich the know-how of recycled gypsum re-incorporation at high levels, especially concerning its inclusion in the manufacturing of more gypsum products, and to investigate the optimum solutions regarding equipment modifications and investments. It is also stated that since the production trials only lasted for a short period of time (i.e. a few hours), the process impacts *on a constant basis* still need to be assessed.

Further suggestions include the potential enhancement of the purity of the recycled powder through chemical cleaning methods, although these may add excessive cost that would restrict the further quality improvement of the recycled material, and in respect to silicone, the assessment of the plasterboard waste and the removal of unfit boards upfront in the reclaim process, in order to avoid costly processing techniques for silicone elimination from the powder.

In summary, the overall outcome of the 2nd round of trials as put forward in the questionnaires is that, with the exception of some feeding system capacity limitations and gypsum quality related issues which in certain cases determined the maximum feasible re-incorporation rate, the rest of the problems encountered were more or less overcome *up to the achieved rate and given the quality of the recycled material received during the trials in each case*, with appropriate process adjustments.

4.4 Overview

The potential impact of incorporating recycled gypsum in the plasterboard manufacturing process is multiple and in some cases reinforced by correlated and/or conflicting effects. Many modification options that readily address the impact on individual manufacturing parameters may negatively affect other process variables and may therefore need reconsideration. 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.

The quality of recycled gypsum is obviously the key determinant factor of the impact it has on the process. In this context, the consistency of its characteristics plays a critical role. Quality fluctuations between different batches of recycled material are difficult to avoid given the nature of its sources, but as recycling practices continue to improve they can be kept within a tight range. Naturally, a material of fixed high quality would be most desirable in order to avoid implications for the process.

Even though process effects may be easy to overcome at relatively low recycling levels exploiting the so far experience, recycling at higher levels may require tightening of the existing specifications on waste in order to facilitate re-incorporation and some investment from the manufacturers' part may be needed.

As a general rule, it can be expected that the more the recycled gypsum conforms to the properties of the conventional feedstock used, the less it will affect the manufacturing process. Furthermore, given the individualities in each plant's feedstock mix and process, only a set of *minimum* specifications for recycled gypsum can be established. More specific quality requirements can be arranged by bilateral agreements between manufacturers and recyclers, or alternatively, manufacturers can decide on a new standard feedstock mix of consistent properties with the highest possible incorporation of recycled gypsum that ensures normal plant operation with the new fine-tuned process.

It should be highly noted that the object of this chapter is to list and analyze all *potential* impacts that may arise from the incorporation of high percentages of recycled gypsum in the plasterboard manufacturing process and to link these impacts to their possible causes (i.e. properties of recycled gypsum, technical limitations etc.). However, this is not an all-inclusive list of every parameter important to every plasterboard plant. In practice, the occurrence and the “intensity” of these impacts highly depend on each process’ specific characteristics and many of the described effects are equally relevant to usual fluctuations in the quality of conventional feedstock.

Hence, due to the individualized procedures followed at each plant, GtoG cannot develop a generalised methodology, including standardized plant modifications, for the optimum/highest inclusion percentage of recycled gypsum in the plasterboard manufacturing process. Based on the outcome of the production trials, the specifications for recycled gypsum could be tailored to the needs of each individual manufacturer, largely depending on the standard level of re-incorporation in the plant. However, the experience acquired can provide important guidelines and thus contribute to setting or updating the framework for an EU quality specification that the recycled material is required to have.

5. Property Analysis of Raw Materials and Products

Between February 2014 and January 2015 all the partners involved have sent to LOEMCO samples of the raw materials and plasterboards for 1st and 2nd round of production trials.

The aim of the testing protocol for action B3.1 is to:

- Establish the materials to be tested, participants, testing methods, number of samples, sample size and data delivery procedures
- Determine the recycled gypsum relevant properties
- Verify the properties of the plasterboards obtained by each manufacturer (conventional formula vs. post-consumer recycled gypsum incorporation)

The samples of different raw materials and plasterboards received during the mentioned period are shown in Table 5-1.

Table 5-1 Types of **s**amples received for property analysis

PRODUCT NAME	DEFINITION	CODE
Conventional gypsum	Conventional gypsums used as raw materials at the present day in the plants, whatever their source (i.e.: mined gypsum, FGD, and others). Thus, it includes recycled gypsum obtained inside the plants from the scraps of the actual manufacturing process	GY GY-M: Mined GY-F: FGD GY-R: Internally recycled
Post-consumer recycled gypsum	Gypsum powders coming from deconstruction and demolition practices, after appropriate treatment.	RG
Plasterboards	As produced in each plant • 1st round of production trials (standard composition) • 2nd round of production trials (new composition increasing the post-consumer gypsum content)	PB
Wastepaper	Lining paper obtained from the recycling of plasterboards, whatever the origin (recycled boards from inside the plant or from deconstruction or demolition)	WP

5.1 Test Methods

According to the testing protocol for action B3.1 LOEMCO has characterized every sample received. Every result is interesting to characterize all raw materials used in each production trial. Nevertheless the most relevant samples for the aim of the project are post-consumer recycled gypsum and properties of plasterboards produced in the 2nd trial, in order to study the effect of the recycled gypsum incorporation.

The test methods that have been carried out by product are shown in Tables 5-2 to 5-5.

Table 5-2 Test methods for conventional gypsum (GY)

TEST NAME	TEST METHOD	TEST TYPE
WATER /PLASTER RATIO (Dispersal method)	EN 13279-2:2006 Clause 4.3.2	PHYSICAL
SETTING TIME (Knife method)	EN 13279-2:2006 Clause 4.4.1	PHYSICAL
SIEVE ANALYSIS	EN 13279-2:2006 Clause 4.1	PHYSICAL
FLEXURAL STRENGTH	EN 13279-2:2006 Clause 4.5.4	MECHANICAL
COMPRESSIVE STRENGTH	EN 13279-2:2006 Clause 4.5.5	MECHANICAL
HARDNESS	EN 13279-2:2006 Clause 4.5.3	PHYSICAL
SULPHUR TRIOXIDE CONTENT / EQUIVALENT CALCIUM SULFATE	EN 13279-2:2006 Clause 4.2	CHEMICAL
FREE WATER CONTENTS	UNE 102032	CHEMICAL
BINDED WATER CONTENTS	UNE 102032	CHEMICAL
PURITY INDEX	UNE 102032	CHEMICAL
TOTAL ORGANIC CARBON (TOC)	EN 13639	CHEMICAL
WATER SOLUBLE MAGNESIUM SALTS (MgO)	Adaptation EN 772-5	CHEMICAL
WATER SOLUBLE SODIUM SALTS (Na2O)	Adaptation EN 772-5	CHEMICAL
WATER SOLUBLE POTASSIUM SALTS (K2O)	Adaptation EN 772-5	CHEMICAL
SOLUBLE CHLORIDE CONTENTS (Cl)	UNE 102032	CHEMICAL
pH	UNE 102032	CHEMICAL
COLOR (WHITENESS)	UNE 80117	PHYSICAL

Table 5-3 Test methods for post-consumer recycled gypsum (RG) (in addition of those shown in Table 5-2)

TEST NAME	TEST METHOD	TEST TYPE
TRACE ELEMENTS (As, Be, Pb, Cd, Cr, Co, Cu, Mn, Ni, Hg, Se, Te, Tl, V, Zn)	INDUCTIVELY COUPLED PLASMA SPECTROSCOPY (ICP)	ANALYTICAL
ASBESTOS	X-RAY DIFFRACTION + MICROSCOPY	ANALYTICAL

Table 5-4 Test methods for plasterboard (PB)

TEST NAME	TEST METHOD	TEST TYPE
FLEXURAL STRENGTH	EN 520:2005+A1:2010 Clause 5.7	MECHANICAL
TOTAL WATER ABSORPTION	EN 520:2005+A1:2010 Clause 5.9.2	PHYSICAL
SURFACE WATER ABSORPTION	EN 520:2005+A1:2010 Clause 5.9.1	PHYSICAL
DENSITY	EN 520:2005+A1:2010 Clause 5.11	PHYSICAL
SURFACE HARDNESS (IMPACT RESISTANCE / HARD IMPACT)	EN 520:2005+A1:2010 Clause 5.12	PHYSICAL

Table 5-5 Test methods for waste paper (WP)

TEST NAME	TEST METHOD	TEST TYPE
GYPSUM CONTENT	INTERNAL METHOD	CHEMICAL

5.2 List of Samples Received and Status of Testing

The samples received per manufacturer and the status of testing for each one are presented in Table 5-6 (updated 29/04/15):

Table 5-6 Samples received per manufacturer and status of testing

Manufacturer	Product		Reception date	Status of testing
1	Stucco		17/02/2014	tested
	WP	Waste paper	17/02/2014	tested
	PB	**GPB - 1st trial**	17/02/2014	tested
	PB	**GPB - 1st trial**	17/02/2014	tested
	RG	Recycled gypsum	08/04/2014	tested
	RG	Recycled gypsum	08/04/2014	tested
	RG	Post-consumer recycled gypsum	02/06/2014	tested
	RG	Post-consumer recycled gypsum	09/06/2014	tested
	PB	**GPB - 2nd trial**	08/09/2014	tested
	PB	**GPB - 2nd trial**	23/09/2014	tested
2	GY-M	Conventional gypsum	07/03/2014	tested
	WP	Waste paper	07/03/2014	tested
	RG	Recycled gypsum	07/03/2014	tested
	PB	**GPB - 1st trial**	08/04/2014	tested

(Cont.)

Manufacturer	Product		Reception date	Status of testing
	PB	**GPB – 2nd trial**	15/01/2015	tested
	RG	Post-consumer recycled gypsum	15/01/2014	tested
3	PB	**GPB - 1st trial**	31/03/2014	tested
	WP	Waste paper	31/03/2014	tested
	WP	Waste paper	31/03/2014	tested
	GY-F	Conventional gypsum	31/03/2014	tested
	GY-R	Conventional gypsum	31/03/2014	tested
	RG	Post-consumer recycled gypsum	05/11/2014	tested
	RG	Post-consumer recycled gypsum	05/11/2014	tested
	RG	Post-consumer recycled gypsum	05/11/2014	tested
	RG	Post-consumer recycled gypsum	05/11/2014	tested
	RG	Post-consumer recycled gypsum	05/11/2014	tested
	WP	Waste paper	05/11/2014	tested
	WP	Waste paper	05/11/2014	tested
	WP	Waste paper	05/11/2014	tested
	GY-F	Conventional gypsum	05/11/2014	tested
	PB	**GPB - 2nd trial**	05/11/2014	tested
4	RG	Recycled gypsum	04/04/2014	tested
	GY-R	Conventional gypsum	04/04/2014	tested
	GY-M	Conventional gypsum	04/04/2014	tested
	WP	Waste paper	04/04/2014	tested
	PB	**GPB - 1st trial**	11/04/2014	tested
	GY-M	Conventional gypsum	07/01/2014	tested
	WP	Waste paper	07/01/2015	not tested
	WP	Waste paper	07/01/2015	not tested
	WP	Waste paper	07/01/2015	not tested
	PB	**GPB - 2nd trial**	07/01/2015	tested
	RG	Post-consumer recycled gypsum	09/01/2015	tested
	RG	Post-consumer recycled gypsum	09/01/2015	tested
5	Stucco		08/04/2014	tested
	PB	**GPB - 1st trial**	08/04/2014	tested
	RG	Post-consumer recycled gypsum	03/06/2014	tested
	GY-M	Conventional gypsum	25/08/2014	tested
	Stucco		09/01/2015	not tested
	RG	Post-consumer recycled gypsum	09/01/2015	tested
	GY-M	Conventional gypsum	09/01/2015	tested
	PB	**GPB - 2nd trial**	28/01/2015	tested

5.3 Average Results

To preserve confidentiality of results for each partner the following tables present the average values of each type of sample received until June 2014.

Regarding the gypsum samples, two groups have been distinguished according to their source:

- Conventional gypsum samples (mined, FGD, internally recycled) (GY)
- Post-consumer recycled gypsum samples from C&D waste (RG)

The results presented in Tables 5-7 and 5-8 are preliminary values. Definitive results may vary after new agreements about changes in test procedures and sample selection.

Table 5-7 Test results for conventional gypsum (GY) samples (average values of 7 samples)

Test name	Test method	Average value	Units
Water/Plaster Ratio	EN 13279-2:2006 Clause 4.3.2	0,93	----
Setting time	EN 13279-2:2006 Clause 4.4.1	233	min
Sieve Analysis	EN 13279-2:2006 Clause 4.1		
5000 microns sieve	EN 13279-2:2006 Clause 4.1	0	% retained
1500 microns sieve	EN 13279-2:2006 Clause 4.1	0	% retained
800 microns sieve	EN 13279-2:2006 Clause 4.1	1	% retained
200 microns sieve	EN 13279-2:2006 Clause 4.1	23	% retained
100 microns sieve	EN 13279-2:2006 Clause 4.1	21	% retained
Flexural strength	EN 13279-2:2006 Clause 4.5.4	2,7	N/mm^2
Compressive strength	EN 13279-2:2006 Clause 4.5.5	7,0	N/mm^2
Hardness	EN 13279-2:2006 Clause 4.5.3	10,7	N/mm^2
Color (whiteness)	UNE 80117:2002	90,0	L* parameter
Sulphur trioxide content	EN 13279-2:2006 clause 4.2	42,25	%
Equivalent calcium sulfate	EN 13279-2:2006 clause 4.2	71,63	%
Free water content	UNE 102032:1999	6,30	%
Binded water content	UNE 102032:1999	18,89	%
Purity index	UNE 102032:1999	90,52	%
Total Organic Carbon (TOC)	EN 13639:2002	0,85	%
Water soluble magnesium salts (MgO)	EN 772-5:2001 (modified)	0,01	%
Water soluble sodium salts (Na_2O)	EN 772-5:2001 (modified)	0,02	%
Water soluble potassium salts (K_2O)	EN 772-5:2001 (modified)	0,01	%
Soluble chloride content (Cl)	UNE 102032:1999	0,04	%
pH	UNE 102032:1999	8,36	----
Trace elements	ICP-OES		
As	ICP-OES	< LOD	mg/kg
Be	ICP-OES	3	mg/kg
Pb	ICP-OES	5	mg/kg
Cd	ICP-OES	< LOD	mg/kg
Cr	ICP-OES	6	mg/kg
Co	ICP-OES	< LOQ	mg/kg
Cu	ICP-OES	< LOQ	mg/kg

Mn	ICP-OES	39	mg/kg
Ni	ICP-OES	4	mg/kg
Hg	ICP-OES	< LOQ	mg/kg
Se	ICP-OES	< LOD	mg/kg
Te	ICP-OES	< LOD	mg/kg
Tl	ICP-OES	< LOQ	mg/kg
V	ICP-OES	43	mg/kg
Zn	ICP-OES	22	mg/kg
Asbestos content	X-Ray diffraction+microscopy	NO	

LOD: Limit Of Detection: 1 mg/kg - LOQ: Limit Of Quantification: 4 mg/kg

Table 5-8 Test results for post-consumer recycled gypsum (RG) samples (average values of 5 samples)

Test name	Test method	Average value	Units
Water/Plaster Ratio	EN 13279-2:2006 Clause 4.3.2	0,77	----
Setting time	EN 13279-2:2006 Clause 4.4.1	325	min
Sieve Analysis	EN 13279-2:2006 Clause 4.1		
5000 microns sieve	EN 13279-2:2006 Clause 4.1	0	% retained
1500 microns sieve	EN 13279-2:2006 Clause 4.1	0	% retained
800 microns sieve	EN 13279-2:2006 Clause 4.1	6	% retained
200 microns sieve	EN 13279-2:2006 Clause 4.1	38	% retained
100 microns sieve	EN 13279-2:2006 Clause 4.1	31	% retained
Flexural strength	EN 13279-2:2006 Clause 4.5.4	2,5	N/mm^2
Compressive strength	EN 13279-2:2006 Clause 4.5.5	6,6	N/mm^2
Hardness	EN 13279-2:2006 Clause 4.5.3	6,6	N/mm^2
Color (whiteness)	UNE 80117:2002	90,5	L* parameter
Sulphur trioxide content	EN 13279-2:2006 clause 4.2	38,52	%
Equivalent calcium sulfate	EN 13279-2:2006 clause 4.2	65,48	%
Free water content	UNE 102032:1999	5,86	%
Binded water content	UNE 102032:1999	17,98	%
Purity index	UNE 102032:1999	83,46	%
Total Organic Carbon (TOC)	EN 13639:2002	0,66	%
Water soluble magnesium salts (MgO)	EN 772-5:2001 (modified)	0,01	%
Water soluble sodium salts (Na_2O)	EN 772-5:2001 (modified)	0,02	%
Water soluble potassium salts (K_2O)	EN 772-5:2001 (modified)	0,02	%
Soluble chloride content (Cl)	UNE 102032:1999	0,01	%
pH	UNE 102032:1999	8,7	----
Trace elements	ICP-OES		
As	ICP-OES	< LOQ	mg/kg
Be	ICP-OES	4	mg/kg
Pb	ICP-OES	< LOQ	mg/kg
Cd	ICP-OES	1	mg/kg
Cr	ICP-OES	21	mg/kg
Co	ICP-OES	3	mg/kg

Cu	ICP-OES	11	mg/kg
Mn	ICP-OES	63	mg/kg
Ni	ICP-OES	13	mg/kg
Hg	ICP-OES	< LOQ	mg/kg
Se	ICP-OES	< LOD	mg/kg
Te	ICP-OES	< LOD	mg/kg
Tl	ICP-OES	< LOD	mg/kg
V	ICP-OES	50	mg/kg
Zn	ICP-OES	45	mg/kg
Asbestos content	X-Ray diffraction+microscopy	NO	

LOD: Limit Of Detection: 1 mg/kg - LOQ: Limit Of Quantification: 4 mg/kg

The above results for powder samples were discussed between partners and some unexpected results were found for some determinations. The explanations of these deviations between results were:

- Different analysis methods followed by partners' laboratories
- Differences in the source of the samples sent to LOEMCO (some were raw gypsum waste and not recycled gypsum waste from the recyclers)
- Differences in the sample preparation between laboratories

To standardize methods between all partners and the type of samples to test, new methods of preparation and testing were proposed, focusing on conventional gypsum and recycled gypsum samples from both 1st and 2nd trials. After the B2.2 meeting celebrated on 20/01/2015 it was agreed that LOEMCO should retest the mentioned samples following a new testing protocol. These new test methods are included in the VGB-M 701 Instruction Sheet for Analysis of FGD gypsum, published by the VGB PowerTech e.V., the European Technical Association for Power and Heat Generation in collaboration with the Federal Association of the Gypsum Industry (Bundesverband der Gipsindustrie e.V.). The new testing protocol according to VGB-M 701 Instruction considers the tests of Table 5-9.

Table 5-9 Testing Protocol VGB-M 701

Parameter	Test method	Test type
Particle size (granulometry)	UNE-EN 933-1	Physical
Humidity	VGB serial number 1	Chemical
Purity (Calcium Sulphate CaSO4 2H2O)	VGB serial number 2.3	Chemical
Total Organic Carbon (TOC)	UNE EN 13137	Chemical
Magnesium salts, walter soluble	VGB serial number 8.1.2	Chemical
Sodium salts, water soluble	VGB serial number 8.2.2	Chemical
Potassium salts, water soluble	VGB serial number 8.3.2	Chemical
Soluble Chloride	VGB serial number 8.8.3	Chemical
pH	VGB serial number 4	Chemical
Trace elements (As, Be, Pb, Cd, Cr, Co, Cu, Mn, Ni, Hg, Se, Te, Tl, V, Zn)	DIN EN ISO 11885 (ICP-OES)	Analytical
Radioactivity (^{40}K; ^{137}Cs; ^{226}Ra; ^{232}Th)	Internal procedure	Analytical

Additional radioactivity tests were included only for the 2nd trial samples (for both conventional and recycled gypsum).

Finally, the samples from the 1st and 2nd trials selected for testing following the new methods by type of material are shown in Table 5-10.

Table 5-10 Selected samples tested according to VGB-M 701 protocol by type of material

Material		1st trial	2nd trial
Recycled gypsum	RG	3	10
Conventional gypsum	GY-M	2	2
	GY-F	2	1
	GY-R	1	0
Total		8	13

The new tests focus on recycled gypsum samples from CDW since the main objective is to establish specification values for this material. In addition, internally recycled gypsum (from the production process) and samples of conventional gypsum, used as common raw materials, were also tested in order to have reference values. Final results of gypsum powder samples selected in January 2015 following the new testing protocol are presented in Tables 5-11 and 5-12. In order to illustrate the appearance of the material, some pictures of the recycled gypsum samples tested are shown in Figures 5-1 and 5-2.

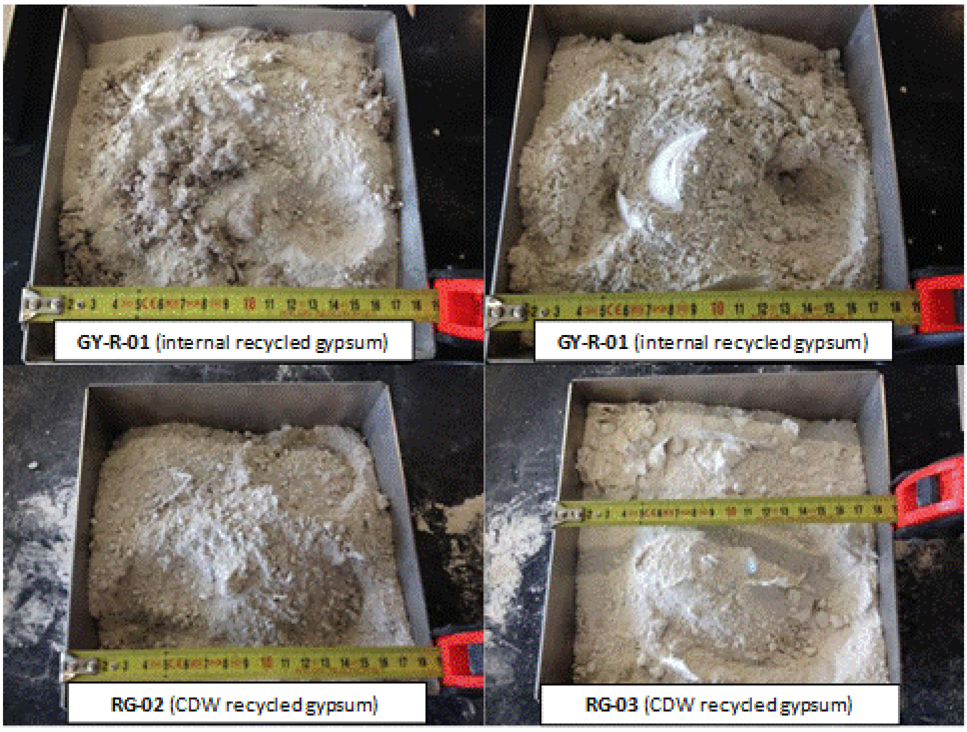

Figure 5-1 Recycled gypsum samples from the 1st round of trials

It is easy to identify different kind of fibers even in internally recycled samples. Small pieces of paper are more likely to be found in the CDW recycled material.

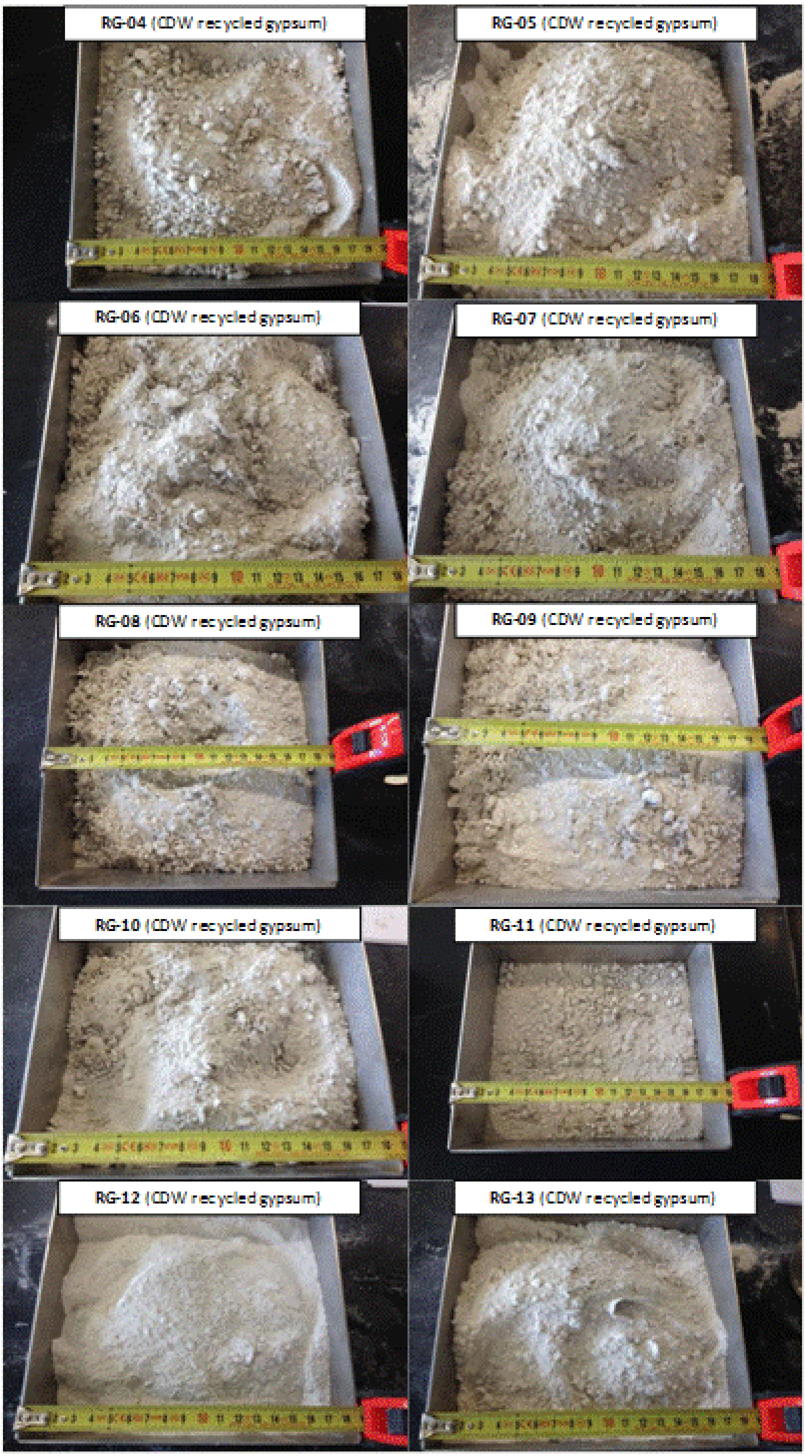

Figure 5-2 Recycled gypsum samples from the 2nd round of trials

All of these samples for the 2nd trial are recycled gypsum from CDW and it is easy to appreciate in some of them fibers and small pieces of paper. On the other hand some samples look very clean and basically fiber and paper free.

Table 5-11 Individual values for technical parameters (1st and 2nd trials)

Parameter	Test method	Powder spec	1st TRIAL								2nd TRIAL												
			Conventional gypsum				Recycled gypsum (internal and C&D waste)				Conventional gypsum			Recycled gypsum (internal and C&D waste)									
			GY-F-01	GY-F-02	GY-M-01	GY-M-02	GY-R-01	RG-01	RG-02	RG-03	GY-F-03	GY-M-03	GY-M-04	RG-04	RG-05	RG-06	RG-07	RG-08	RG-09	RG-10	RG-11	RG-12	RG-13
Max. size measured (mm)	UNE-EN 933-1	----	< 0,1	0,1	20	----	4	2	4	14	0,1	20	----	4	8	8	4	14	8	14	8	8	8
Particles < 4 mm (%)	UNE-EN 933-1	----	100	100	67	----	99	100	96	91	100	61	----	89	92	95	96	92	97	92	83	95	90
Free moisture	VGB serial number 1	< 10%	0,05	6,64	4,89	0,08	1,00	0,51	2,50	9,94	6,85	4,52	0,12	1,92	0,27	9,47	9,40	10,46	11,74	17,14	4,14	4,50	7,84
Purity ($CaSO_4$ $2H_2O$)	VGB serial number 2.3	> 80%	96,41	93,89	89,59	89,01	89,85	86,95	87,70	88,78	93,40	90,67	91,42	79,83	82,97	90,22	90,64	90,20	88,72	89,78	83,06	89,26	88,25
TOC	Gigt 3.1.3.2 DepV DIN EN 13137	< 1.5%	0,01	0,16	0,04	0,03	0,83	3,13	0,75	0,44	0,22	0,03	0,04	0,63	0,82	0,79	0,75	0,83	0,84	0,84	0,78	0,30	0,19
Magnesium salts, walter sol.	VGB serial number 8.1.2	< 0.1%	0,006	0,012	0,009	0,004	0,012	0,010	0,029	0,012	0,012	0,008	0,005	0,038	0,013	0,013	0,013	0,012	0,012	0,033	0,019	0,009	0,008
Sodium salts, walter sol.	VGB serial number 8.2.2	< 0.06%	0,004	0,007	0,004	0,002	0,019	0,066	0,019	0,023	0,008	0,004	0,003	0,026	0,023	0,019	0,019	0,019	0,018	0,017	0,028	0,021	0,019
Potassium salts, water sol.	VGB serial number 8.3.2	< 0.05%	0,001	0,003	0,003	0,001	0,006	0,034	0,012	0,011	0,003	0,003	0,004	0,021	0,024	0,007	0,007	0,007	0,006	0,007	0,020	0,036	0,007
Sol. Chloride	VGB serial number 8,8,3	< 0.02%	0,002	0,005	0,006	0,001	0,011	0,124	0,013	0,008	0,004	0,006	0,003	0,009	0,009	0,009	0,012	0,010	0,012	0,014	0,019	0,007	0,009
pH	VGB serial number 4	7-9	6,50	7,03	8,10	7,42	8,51	8,35	8,22	7,87	7,28	8,05	7,45	8,91	8,82	7,78	7,62	7,56	7,53	8,42	8,43	8,34	7,80

GYPSUM TO GYPSUM

Table 5-12 Individual values for toxicological parameters (1st and 2nd trials)

Element [mg/kg]	Test method	Proposed limits		1st TRIAL								2nd TRIAL												
		BV Gips DE	Quality Protocol UK	Conventional gypsum				Recycled gypsum (production and C&D waste)				Conventional Gypsum			Recycled gypsum (production and C&D waste)									
				GY-F-01	GY-F-02	GY-M-01	GY-M-02	GY-R-01	RG-01	RG-02	RG-03	GY-F-03	GY-M-03	GY-M-04	RG-04	RG-05	RG-06	RG-07	RG-08	RG-09	RG-10	RG-11	RG-12	RG-13
As	DIN EN ISO 11885 Determination of selected elements ICP-OES (acc to DepV)	< 4	5,23	< 0,21	< 0,21	< 0,21	< 0,21	< 0,21	< 0,21	< 0,21	< 0,21	< 0,21	< 0,21	< 0,21	< 0,21	< 0,21	< 0,21	< 0,21	< 0,21	< 0,21	< 0,21	< 0,21	< 0,21	< 0,21
Be		< 0,7	-	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01
Pb		< 22	31,9	< 0,18	< 0,18	< 0,18	< 0,18	< 0,18	< 0,18	< 0,18	< 0,18	< 0,18	< 0,18	< 0,18	130,40	< 0,18	< 0,18	< 0,18	< 0,18	< 0,18	< 0,18	< 0,18	< 0,18	< 0,18
Cd		< 0,5	0,3	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01
Cr		< 25	17,9	< 0,01	1,42	< 0,01	0,85	1,39	< 0,02	5,97	1,37	< 0,01	< 0,01	0,78	4,85	3,47	2,06	1,10	2,03	1,79	2,34	5,94	1,22	< 0,02
Co		< 4	-	< 0,01	< 0,01	< 0,01	< 0,01	< 0,02	< 0,02	< 0,01	< 0,02	< 0,01	< 0,02	< 0,01	< 0,02	2,61	< 0,02	< 0,02	< 0,02	< 0,02	< 0,02	< 0,02	< 0,02	< 0,02
Cu		< 14	32,8	< 0,01	< 0,01	< 0,01	< 0,01	< 0,01	< 0,02	< 0,02	< 0,01	< 0,01	< 0,01	< 0,01	4,59	< 0,01	< 0,02	< 0,02	< 0,02	< 0,02	< 0,02	< 0,02	4,13	< 0,02
Mn		< 200	2,412	16,10	53,40	18,80	43,80	25,23	52,83	33,90	14,82	52,80	17,40	62,20	56,10	50,60	26,20	21,10	25,40	24,00	26,08	52,80	10,24	20,40
Ni		< 13	7,31	< 0,01	< 0,01	< 0,01	< 0,01	7,52	40,50	12,30	7,64	< 0,01	< 0,01	< 0,01	30,70	31,40	7,91	8,51	10,40	8,60	2,88	31,60	11,30	11,10
Se		< 16	7,37	< 0,37	< 0,37	< 0,37	< 0,37	< 0,37	< 0,37	< 0,37	< 0,37	< 0,37	< 0,37	< 0,37	< 0,37	< 0,37	< 0,37	< 0,37	< 0,37	< 0,37	< 0,37	< 0,37	< 0,37	< 0,37
Te		< 0,3	-	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05	< 0,05
Tl		< 0,4	-	< 0,12	< 0,12	< 0,12	< 0,12	< 0,12	< 0,12	< 0,12	< 0,12	< 0,12	< 0,12	< 0,12	< 0,12	< 0,12	< 0,12	< 0,12	< 0,12	< 0,12	< 0,12	< 0,12	< 0,12	< 0,12
V		< 26	-	4,11	2,74	2,96	3,11	4,37	5,99	7,36	6,07	1,03	4,03	5,44	4,58	4,61	4,50	3,54	3,99	4,32	5,09	7,42	3,70	5,29
Zn		< 50	40,3	4,30	15,30	4,19	4,31	15,50	6,39	29,54	39,52	16,90	3,94	5,32	52,90	31,29	18,41	18,31	13,96	17,24	16,67	43,11	16,02	13,68
Hg	DINEN 1483 AAS-DINEN 12338- Merury process after enrichment by amalgation. DIN ISO 1785 atomic fluorescnce spectrometry (acc to MatelVO)	< 1,3	< 2	0,20	0,43	<0,05	<0,05	0,30	0,08	0,23	<0,05	0,39	<0,05	<0,05	0,21	0,21	0,28	0,29	0,29	0,31	0,29	0,21	<0,05	<0,05
Asbestos content	X-ray diffraction	Free of asbestos (YES / NO)		YES	YES	YES	YES	YES	YES	YES	----	YES	----	----	YES	YES	YES	YES	YES	YES	YES	----	----	----
Radioactivity Index	RP 112 Document (EC)	< 0,5		----	----	----	----	----	----	----	----	< 0,02	< 0,05	< 0,07	< 0,14	< 0,17	< 0,04	< 0,04	< 0,05	< 0,05	< 0,04	< 0,08	< 0,06	< 0,07

Plasterboard samples of the 1st trial were received during the first half of 2014. Samples of the 2nd trial were received between June 2014 and January 2015. Most of them were received cut as defined in the testing protocol but some arrived complete and it was necessary to cut them according to the testing standard. All plasterboard were basically standard type A with thickness of 12,5 mm as tests results will confirm.

Some pictures of the samples received are shown in Figures 5-3 and 5-4.

Figure 5-3 Plasterboard samples from the 1st round of trials

Figure 5-4 Plasterboard samples from the 2nd round of trials

The results for plasterboard samples received during first half of 2014 are shown in Table 5-13. All of them were produced with the current formula by each producer (business as usual). Every producer sent to LOEMCO one sample of plasterboard except producer nº 4 which sent two samples of with its current formula.

Table 5-13 Individual values for plasterboard samples - 1st round of trials

Parameter	Test Method	Units	1st TRIAL					
			Plasterboard Conventional					
			PB 1	PB 2	PB 3	PB 4	PB 5	PB 6
Flexural strength (Longitudinal)	EN 520 2005 +A12010 clause 5.7	N	595	627	577	583	627	631
Flexural strength (Transversal)	EN 520 2005 +A12010 clause 5.7	N	233	224	238	215	245	224
Total water absorption	EN 520-2005+A12010 clause 5.9.2	%	32	33	44	31	35	26
Surface absorption (Face)	EN 5202005+A.1 2010 clause 5.9.2	g/m^2	189	170	212	160	172	188
Surface absorption (Back)	EN 5202005+A.1 2010 clause 5.9.2	g/m^2	585	184	414	160	157	227
Density	EN 520 2005+A1 2010 clause 5.11	kg/m^3	732	698	644	713	718	705
Surface hardness (impact resistance/hard impact)	EN 520 2005+A1:2010 clause 5.12	mm	17	18	19	11	17	17

Producer 1	Producer 2	Producer 3	Producer 4	Producer 5

For confidentiality reasons the name of each producer has been anonymized. Colors have been used to identify the individual results and to compare the results of each producer before (1st trial) and after the reincorporation (2nd trial).

During the second half of 2014 and early 2015, producers manufactured plasterboards increasing the content of recycled gypsum from C&D waste. Although the target value was 30% the range of reincorporation content finally was between 20 to 30%.

For this 2nd trial two producers sent to LOEMCO duplicate samples of modified plasterboards and all of them were tested to gather as much data as possible. The results are shown in Table 5-14.

GYPSUM TO GYPSUM

Table 5-14 Individual values for plasterboard samples – 2nd round of trials

Parameter	Test Method	Units	2nd TRIAL						
			Plasterboard Modified						
			PB 7	PB 8	PB 9	PB 10	PB 11	PB 12	PB 13
Flexural strength (Longitudinal)	EN 520 2005 +A12010 clause 5.7	N	593	554	548	581	619	610	608
Flexural strength (Transversal)	EN 520 2005 +A12010 clause 5.7	N	353	218	256	218	217	240	242
Total water absorption	EN 520-2005+A12010 clause 5.9.2	%	35	46	32	32	32	27	27
Surface absorption (Face)	EN 5202005+A.1 2010 clause 5.9.2	g/m^2	166	262	197	179	180	183	187
Surface absorption (Back)	EN 5202005+A.1 2010 clause 5.9.2	g/m^2	183	239	276	179	189	183	187
Density	EN 520 2005+A1 2010 clause 5.11	kg/m^3	683	663	724	716	714	685	669
Surface hardness (impact resistance/hard impact)	EN 520 2005+A1:2010 clause 5.12	mm	12	10	10	11	11	18	17

Producer 1	Producer 2	Producer 3	Producer 4	Producer 5

For the 5 samples of waste paper tested an average of 20% of gypsum content has been determined (Table 5-15). Since a future separation process of the gypsum and paper seems to be difficult no more testing was requested so far for this type of samples received in the laboratory.

Table 5-15 Test results for waste paper (WP) samples (average values of 5 samples)

Test name	Test method	Average value	Units
Gypsum content in WP	Internal procedure	20,3	%

5.4 Discussion of Results

5.4.1 Conventional Gypsum Powder Results

As expected, all the conventional gypsum samples results comply with the limits proposed and could be used as reference values to assess recycled gypsum results.

5.4.2 Recycled Gypsum Powder Results

For the samples of 1st trial tested the sample RG-01 exceeds the proposed limits for the following parameters:

- TOC
- Water soluble sodium salts
- Soluble Chloride

The RG-01 sample is indeed an internal recycled material from the production process. This could be due to a high paper content of the sample.

Free moisture of samples RG-08, RG-09 and RG-10 is above 10%. This could be a technical problem for the producers since the material will need an additional drying step. The same could be said for samples RG-06 and RG-07 whose free moisture content is close to the 10% limit.

Regarding the toxicological parameters almost all results are below the proposed limit values. These limits were proposed in the B2.2 sub action based on the British Specification PAS 109 for reprocessed gypsum and the “Beckert-Studie” carried out by German Gypsum Association (BV Gips).

Only the nickel content is higher for some samples and the lead content is unexpected for sample RG-04. These samples were retested to double-check nickel and lead values. New results confirm the initial values with minor differences.

The small variation between initial values and new ones are basically due to the fact of having prepared new laboratory samples from the original samples sent by each partner. For the 14 samples retested, new splitting and homogenization have been carried out from the original containers

Definitive results have been included in Table 5-12.

A radiation analysis has been performed only to the samples of 2nd trial (conventional and recycled). The Radiation Protection 112 (RP 112) is a document used by the European Commission to assess limits for building materials. According to RP 112 activity concentration index is calculated for each sample from activity concentrations of Radium, Thorium and Potassium in Bq/kg. Although radioactivity indexes for recycled gypsum samples are substantially higher than the values for conventional gypsum, all results are far below the limit of 0,5 indicated in the RP 112.

Asbestos content where analyzed to the powder samples with an X-Ray diffractometer and the Rietveld method to quantify the content, taking into account it is a semi-quantitative method. All powder samples were tested until the adoption of the new testing protocol after the B2.2 meeting on 20/01/2015. Nevertheless the laboratory keep all the samples received if eventually more asbestos determinations are needed.

5.4.3 Plasterboard Results

The average flexural strength decreases after the reincorporation, specifically the longitudinal strength (Figure 5-5). Nevertheless all of the samples complied with the Type A specification of longitudinal strength (550 N) and it cannot be concluded that the reduction observed in this parameter is caused by the incorporation of recycled gypsum. Plasterboards from producers 1 and 3 are on the limit for this parameter but it should be easy to increase the strength with minor changes in the process.

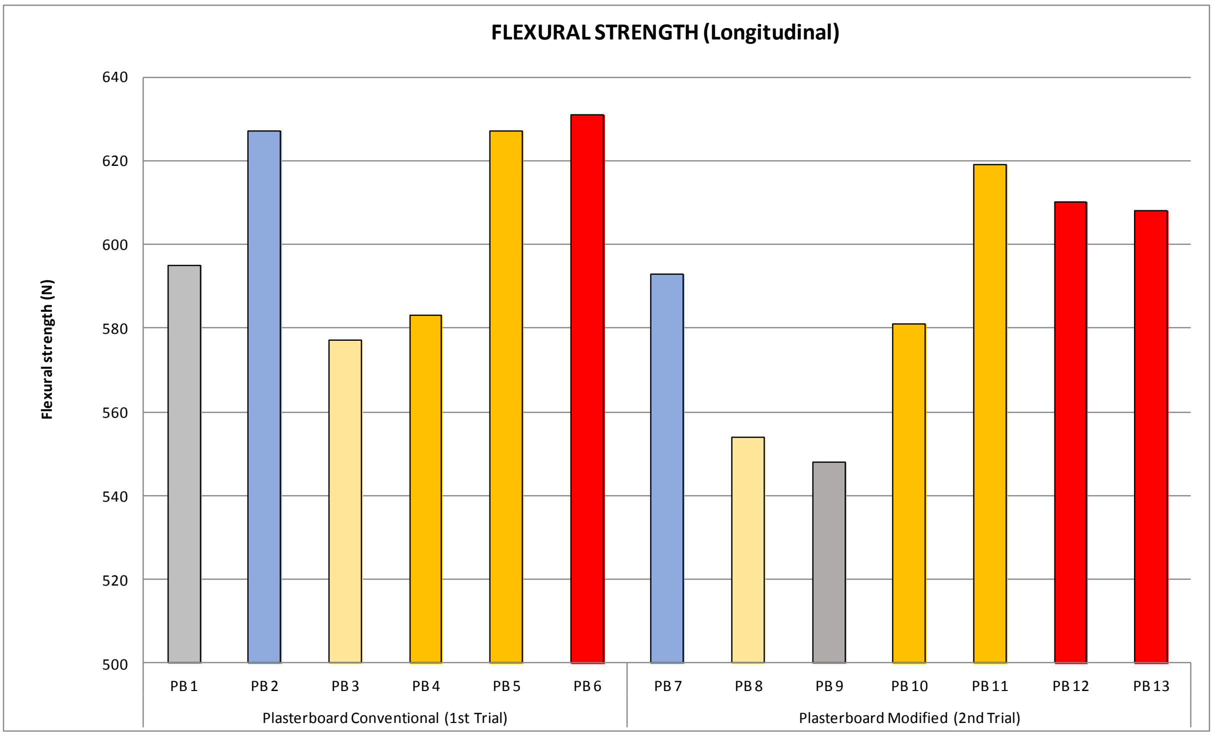

Figure 5-5 Longitudinal **f**lexural strength of plasterboard samples

Transverse strength (Figure 5-6) has been less affected by the reincorporation and all of samples comply with the Type A specification (210 N). In fact some of the 2nd trial samples have higher transverse strength than the 1st trial ones.

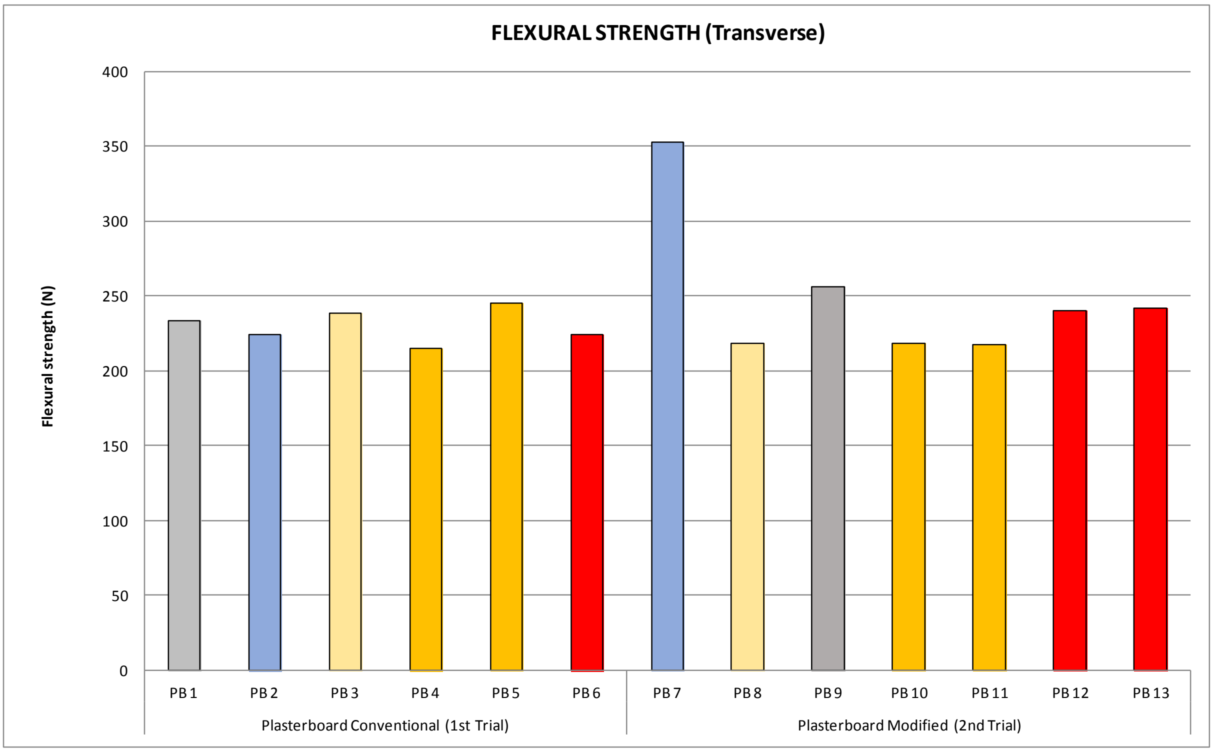

Figure 5-6 Transverse **f**lexural strength of plasterboard samples

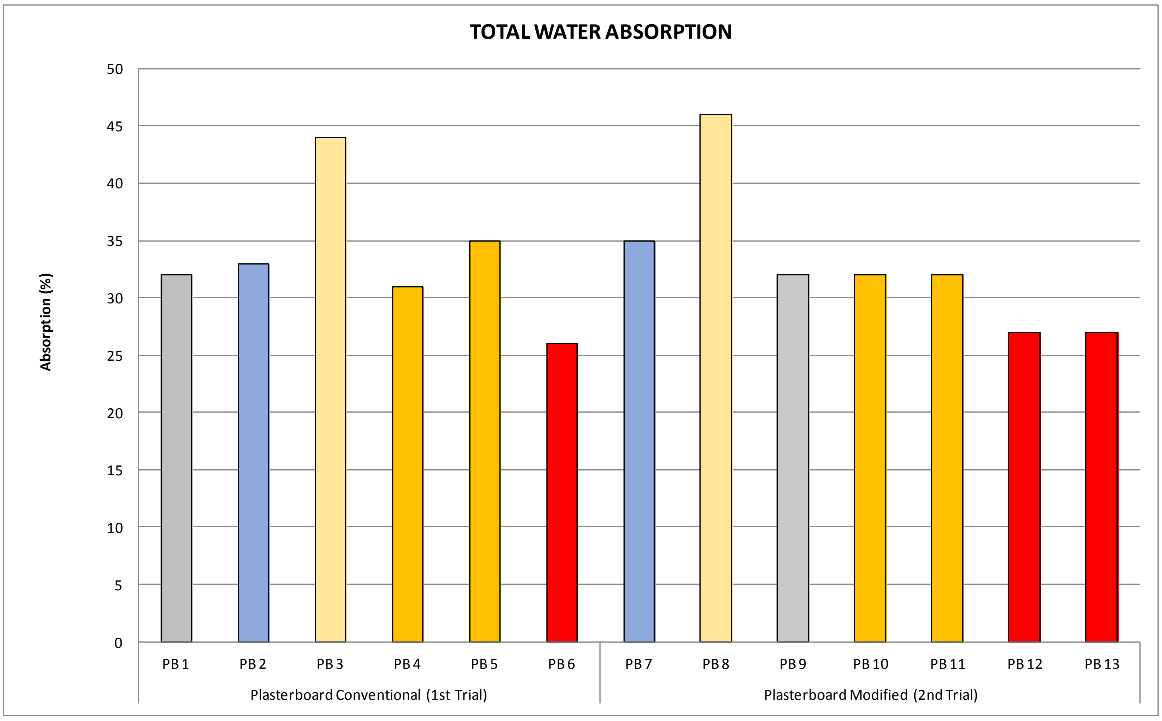

Figure 5-7 Total water absorption of plasterboard samples

Total water absorption (Figure 5-7) has been almost unaffected, just a slight increase for every producer, except for plasterboards of Producer 1 which keep the same total absorption in the 2nd trial.

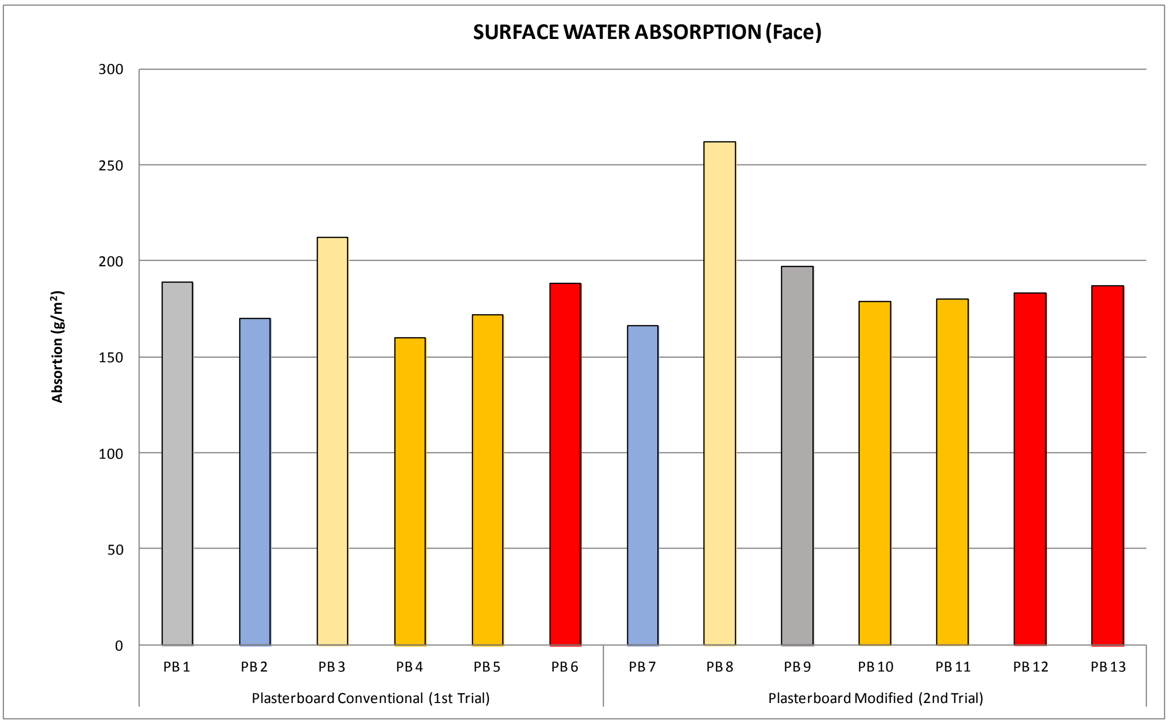

Figure 5-8 Surface water absorption (face) of plasterboard samples

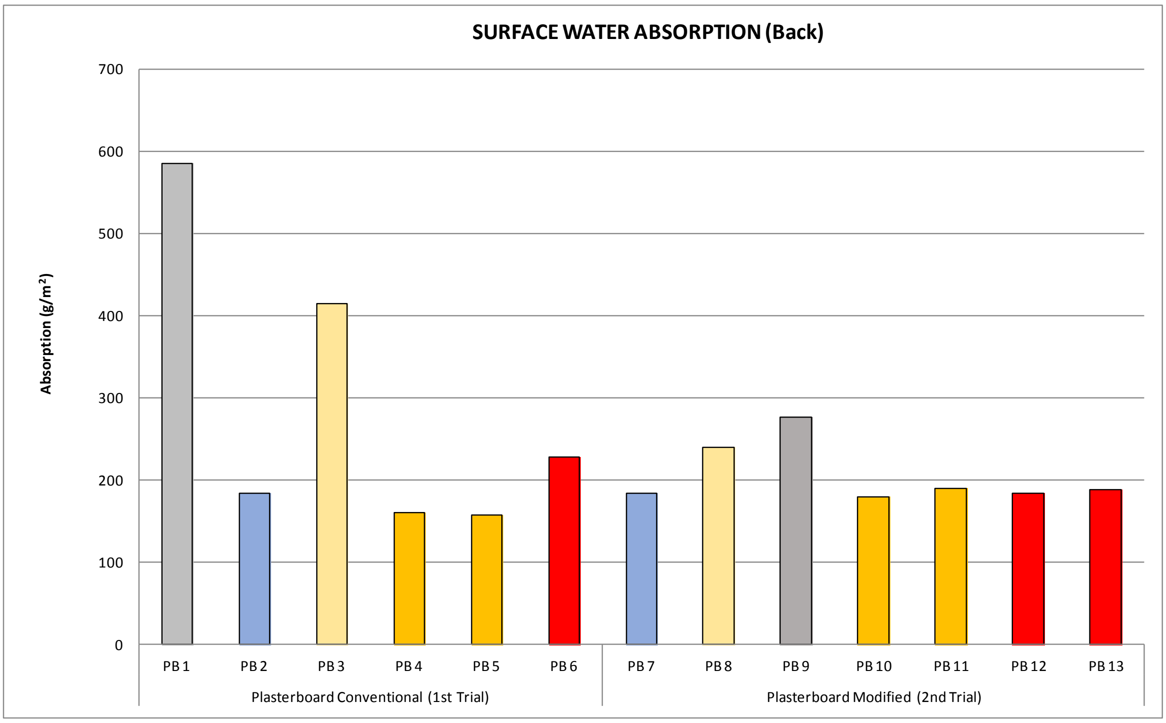

Figure 5-9 Surface water absorption (face) of plasterboard samples

For surface water absorption (face) only the plasterboard of Producer 3 has experienced a significant increase, while the others have a minor increment (Figure 5-8). For surface water absorption (back) plasterboards of Producers 1 and 3 have been experienced a great decrease of this parameter. Minor changes have been observed for the rest of the samples (Figure 5-9).

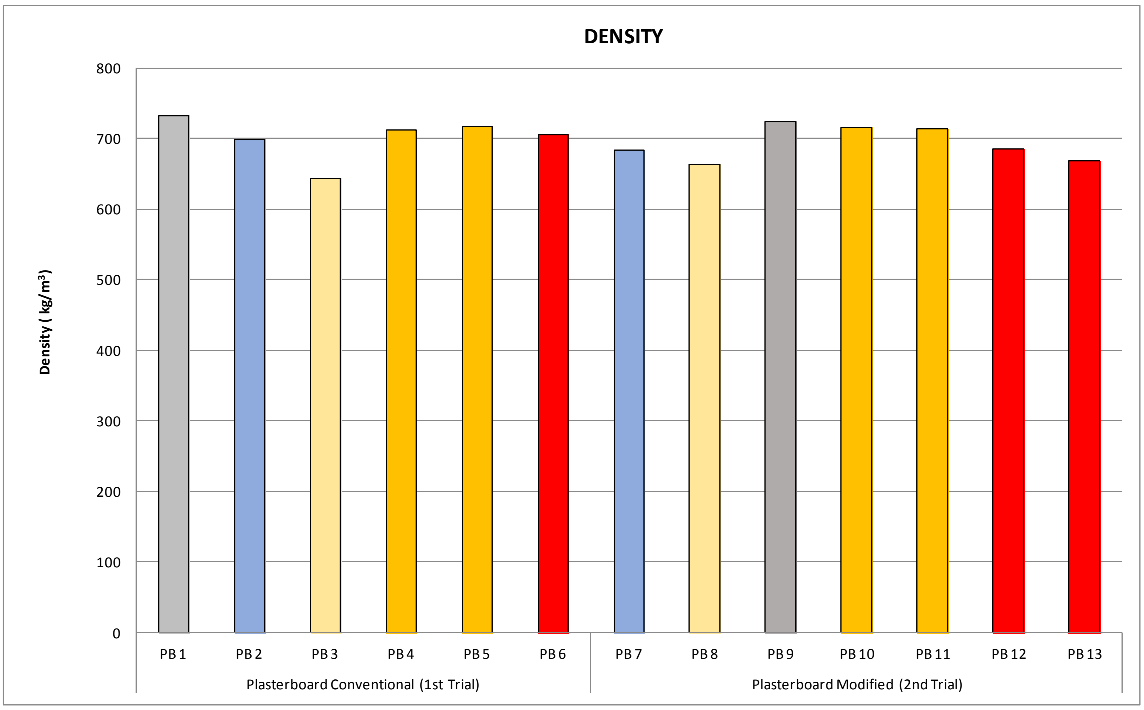

Figure 5-10 Density of plasterboard samples

Density remains almost unaffected in samples of both trials (Figure 5-10).

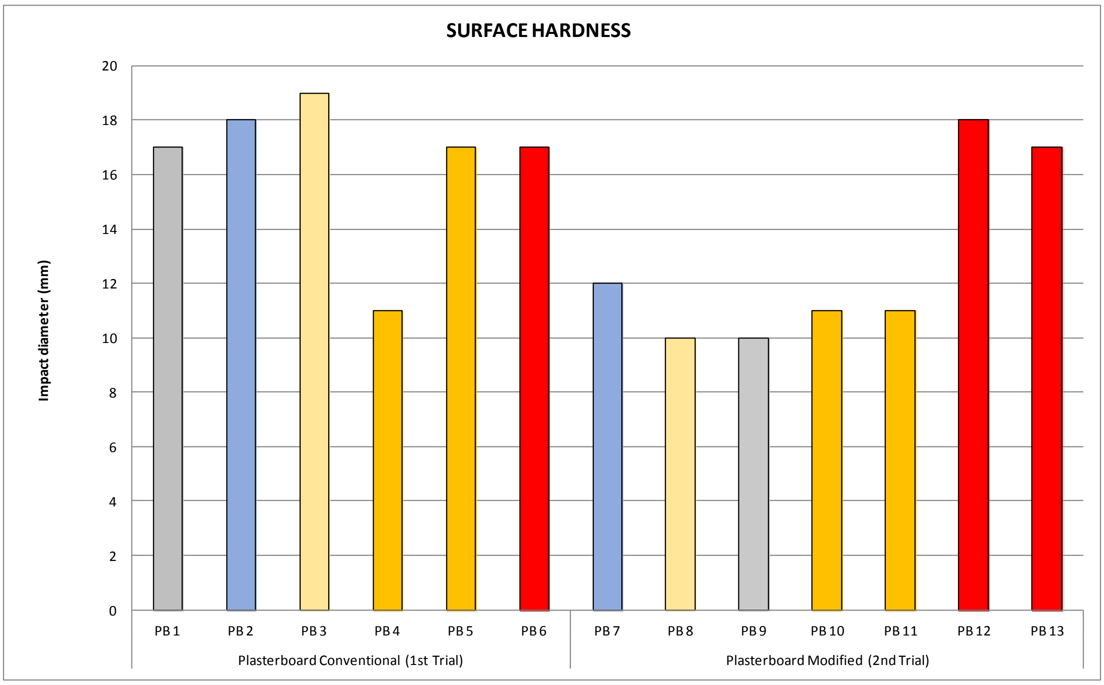

Figure 5-11 Surface hardness of plasterboard samples

Overall, plasterboard samples of the 2nd trial have better surface hardness compared with the values of the 1st trial plasterboards (Figure 5-11). Only 2nd trial plasterboards from Producer 5 had a minor decrease in surface hardness.

5.5 Conclusions

Regarding the specification limits proposed for recycled gypsum samples they seem to be appropriate since only certain limits were exceeded for some of them.

After final test during May, the vast majority of results comply with the proposed limits. Even though some remarks should be mentioned:

- Five samples exceed the limit of 13 mg/kg for nickel content set the “Beckert-Studie” of BV Gips. Maybe another assessment of the nickel limit for recycled gypsum should be considered.
- Nevertheless it should be assessed if proposed limits in Sub-action B2.2 are linked to risk-based threshold values. The assessment is needed to verify that limits exceeded do not necessarily imply a toxicological risk.
- Singular results have been found in one sample exceeding the proposed limits for chloride and TOC determinations. Nevertheless this case should be considered as exceptional since it seems to have high paper content. According to the producer this sample was taken from internal production process, not from C&D waste.

- One of the recycled gypsum samples presented a high figure for lead content but again this should be considered as exceptional. It might be due to an unusual contamination during a previous step or an inappropriate sampling.
- Free moisture content should be monitored since five samples of recycled gypsum presented values around the 10% limit for this parameter.
- Asbestos has not been detected using X-Ray diffraction technique, but to confirm the absence of asbestos complementary technique such as Polarized Light Microscopy should be performed.

It is also important to underline the relevance that test methods and sampling procedures have in trace elements values for recycled gypsum samples. Refined testing methods for recycled gypsum based on the current standards shown in this project will be needed. In addition, standardized methods based on existing standards should be followed for representative laboratory samples.

Regarding plasterboard samples and considering all results, the reincorporation of recycled gypsum does not affect the basic performance of the plasterboards. Differences found in flexural strength and water absorption results could be considered as normal taking into account that formula and batch are different from 1st to 2nd trials. All the samples received from the 1st trial could be classified as 12,5 mm Type A plasterboards according to EN-520 Standard. This classification remains for the samples received from the 2nd trial.

6. Techno-economic Assessment of Recycled Gypsum Reincorporation into the Manufacturing Process

The techno-economic study presented in this chapter is based on the data recorded during the two rounds of production trials in the 5 pilot plants participating in Action B3 of GtoG Project. The study specifically focuses on the manufacturing process of "standard" plasterboard (Type A) and its scope is restricted within the manufacturing plant's borders.

6.1 Study Limitations

6.1.1 Geographical and Temporal Limitations

The production trials were carried out from January 2014 until March 2015 in the 5 plants situated in Belgium, France (2 plants), Germany and the UK. The results therefore refer to this time period and area of study.

Moreover, in order to provide for stable process conditions appropriate for data measurement and recording, a minimum running period of around 12 hours is considered advisable for each trial. However, in some cases the actual reported duration of the trials (i.e. production running at the achieved maximum re-incorporation rate) is shorter (around 2 to 3 hours) due to technical constraints that arose in practice. In any case, the limitation of a short and finite time interval of testing as opposed to manufacturing on a constant basis affects the accuracy of the collected data and, thus, increases the margin of uncertainty of the assessment results.

6.1.2 Confidentiality

The collected data as well as the individual results regarding the impact of the maximized incorporation of recycled gypsum powder in each plant are subject to commercial confidentiality and cannot be reported separately in the study. The presentation of the assessment results is thus limited in reporting only % variations of cost and average values and % variations of energy consumption.

6.1.3 Other Limitations

The limitation of focusing on one specific board type (i.e. standard Type A) is that the results of the techno-economic assessment are applicable only within this context. However, the assessment of the potential impacts on the manufacturing process of this most common plasterboard product is considered an important representative first step before proceeding to investigate the introduction of recycled gypsum use in the manufacturing of further types of gypsum products.

The number of sample cases (five plants) is an important limitation that constrains the level of independence of the results from the process characteristics. It has been previously mentioned that even though all the plants that carried out the trials use typical plasterboard production lines, the five processes are not identical in terms of the feedstock/feedstock mix used, the raw material pre-processing stages, the types and set-up of industrial equipment employed etc. Furthermore, potential differences also exist in the process adjustments and modifications made by each manufacturer as a result of the higher recycled gypsum re-incorporation at the 2nd round of trials. As a consequence, there is "non-homogeneity" in the original collected datasets, which results in inconsistent impact trends on individual parameters among the five separate cases studied, thus limiting the accuracy and increasing the uncertainty range of the generalized average results. A larger sample size would considerably improve the quality of the average results.

Finally, apart from the above mentioned lack of homogeneity in the data, data quality limitations may also arise from potentially poor recording accuracy related with time and technical constraints. In fact, some process parameters have proven difficult to be quantified and measured. Overall however, the present study compiles specific and up-to-date information on the plasterboard manufacturing process and effort has been made to ensure that representative data has been collected for a thorough techno-economic impact assessment.

6.2 System Boundaries

The present techno-economic study aims to assess the impact of the reincorporation of recycled gypsum *on the energy consumption and variable costs of the plasterboard manufacturing process*. In this framework, the system boundaries as shown in Figure 6-1 are defined to include all processes from the entrance of the manufacturing plant until the production of the finished plasterboard. Further upstream and downstream operations such as raw material and recycled gypsum production, product packaging, product distribution etc. do not fall into the scope of study, since their respective energy demands and costs remain unaffected by the introduction of recycled gypsum in the process. For the same reason, labor costs are also excluded.

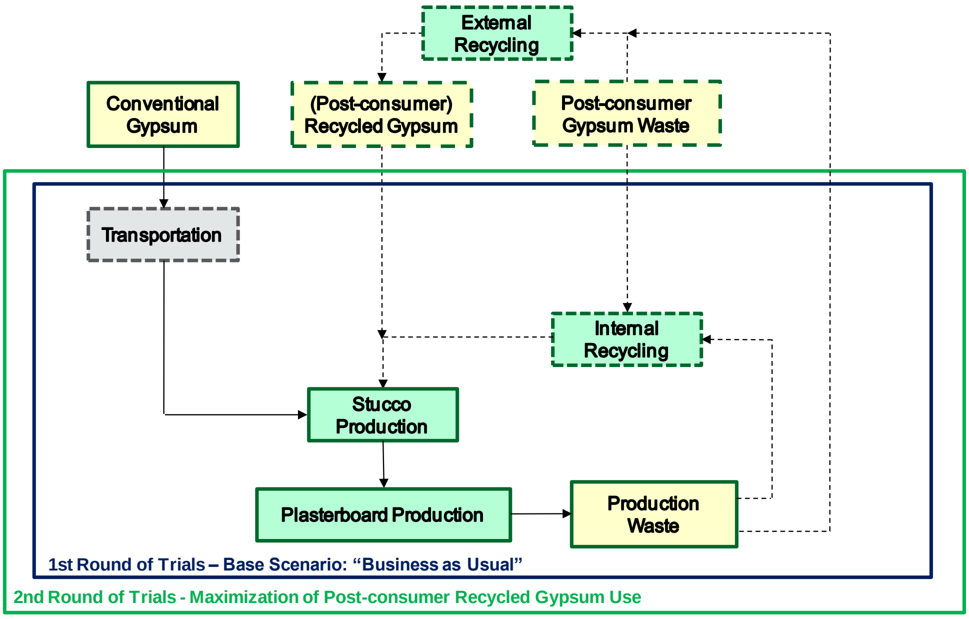

Figure 6-1 Generalized system boundaries of techno-economic assessment

Given that the practices followed in each plant concerning recycled gypsum differ, the above figure depicts a "general scheme" of the system boundaries intending to cover all possible routes. The standard practices followed by all five plants that take part in the project are shown in solid lines, whereas the practices that differ are shown in dashed lines. Two indicative examples of system boundaries are shown in Figure 6-2. Figure 6-2A refers to a plant that as base scenario (1st trials) uses recycled gypsum derived from production waste only, which are recycled internally (i.e. by the plant) and at the 2nd trials introduces and maximizes the use of post-consumer recycled gypsum supplied by an external recycler (third party). Figure 6-2B refers to a plant that has already introduced the use of a standard percentage of recycled gypsum provided by an external recycler, to whom also sends its production waste for recycling (1st trials – base scenario). At the 2nd trials this plant increases the standard percentage of recycled gypsum in feedstock to a maximum.

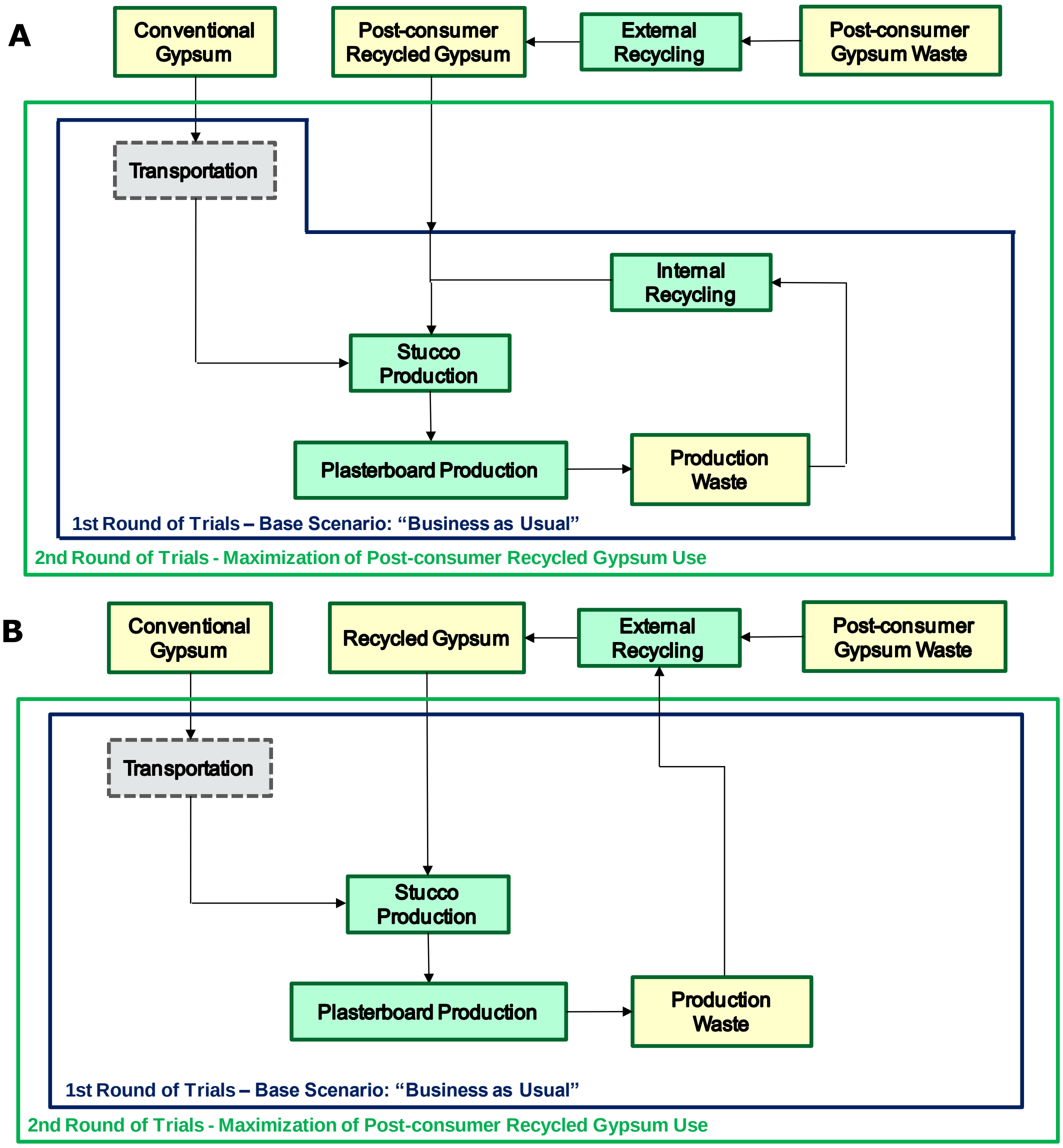

Figure 6-2 Examples of case-specific system boundaries

It is noted that the goal of the 2nd trials in all cases is to introduce and/or maximize the % use of recycled gypsum in feedstock up to the GtoG project's goal of 30% *by increasing the amount derived from post-consumer gypsum waste*.

6.2.1 Transportation

Transportation of raw materials from their source to the plasterboard plant is mostly a responsibility of a third party (raw material supplier, gypsum recycler, gypsum waste collector), but there are cases, such as the transportation 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 plasterboard plant). Shipping costs are always paid by the manufacturer either directly or indirectly, built-in in the price of the material. However, the energy of transportation is not consumed by the manufacturer when the materials are delivered by a third party.

Given that the scope of the techno-economic analysis is to investigate the impact of the use of recycled gypsum *on the plasterboard production process*, transportation of conventional raw materials is included in the system boundaries only when it is carried out by means of the manufacturer. This translates to the following key working assumptions:

- Transportation costs are included in cost calculations.
- Transportation energy consumption is included in energy calculations only when transportation is carried out by the manufacturer. Otherwise this energy is not consumed by the plasterboard producer, so it is not an energy demand of the production process.

Regarding the transportation of recycled gypsum, this is usually delivered to the plants by the recycler companies, which is also the case in all five plants studied, and it is therefore excluded from the system boundaries with respect to energy consumption calculations. However, transportation cost is taken into account as built-in in the price of the recycled material.

The fact that the scope of the study is constrained in this way could be also considered as a limitation. It is regarded, however, that the inclusion of the complete "loop" of transportation (i.e. transportation of conventional raw materials from their source to the plant and of gypsum waste from their sources to the recycling plant and then to the manufacturing plant) falls into the wider scope of a LCA or Carbon Footprint assessment (the object of Sub-action C1.1 of GtoG). On the contrary, the determined scope of Figure 6-1 essentially comprises a generic process model, which enables a more accurate and focused assessment of the potential impacts and benefits strictly within the boundaries of the manufacturing plant, according to the aim and object of the present study.

6.3 Functional Unit

The functional unit for the present study is **1 m^2 of "standard" plasterboard (Type A) with 12.5 mm thickness**, as selected upon agreement with the industrial partners of Action B3 of the GtoG project. This type of plasterboard is the product of the production lines where the pilot projects were carried out. Some key results are also presented per tonne of plasterboard in Appendix II, so that they can be readily linked with results of other Actions of GtoG. It should be also noted that the results refer to 1 m^2 (or 1 tonne where specified) of *net* plasterboard production (i.e. excluding wet and dry production rejects).

6.4 Methodology

The adopted methodology approach is illustrated in Figure 6-3. The variable plasterboard manufacturing costs and the energy consumption are calculated for each of the five processes based on the data collected during the 1st and the 2nd round of production trials respectively using ASPEN Plus 2006 Simulation Software [11], and the impact of the maximization of the % use of recycled gypsum is assessed for each case (plant) by comparing the two sets of results.

Next, in order to present the results in a proper form that conforms to confidentiality related limitations (see Section 6.1.2) two generalized scenarios (one for each round of trials) are developed based on the corresponding data from all five plants; the "Base Scenario – Business as Usual" (1st round of trials) and the "Maximized % Use of Recycled Gypsum Scenario" (2nd round of trials). Variable costs are calculated by multiplying the average consumption of each individual cost element (i.e. conventional raw materials, recycled gypsum, paper, additives, water, fuel and electrical energy) by the respective average price of the element.

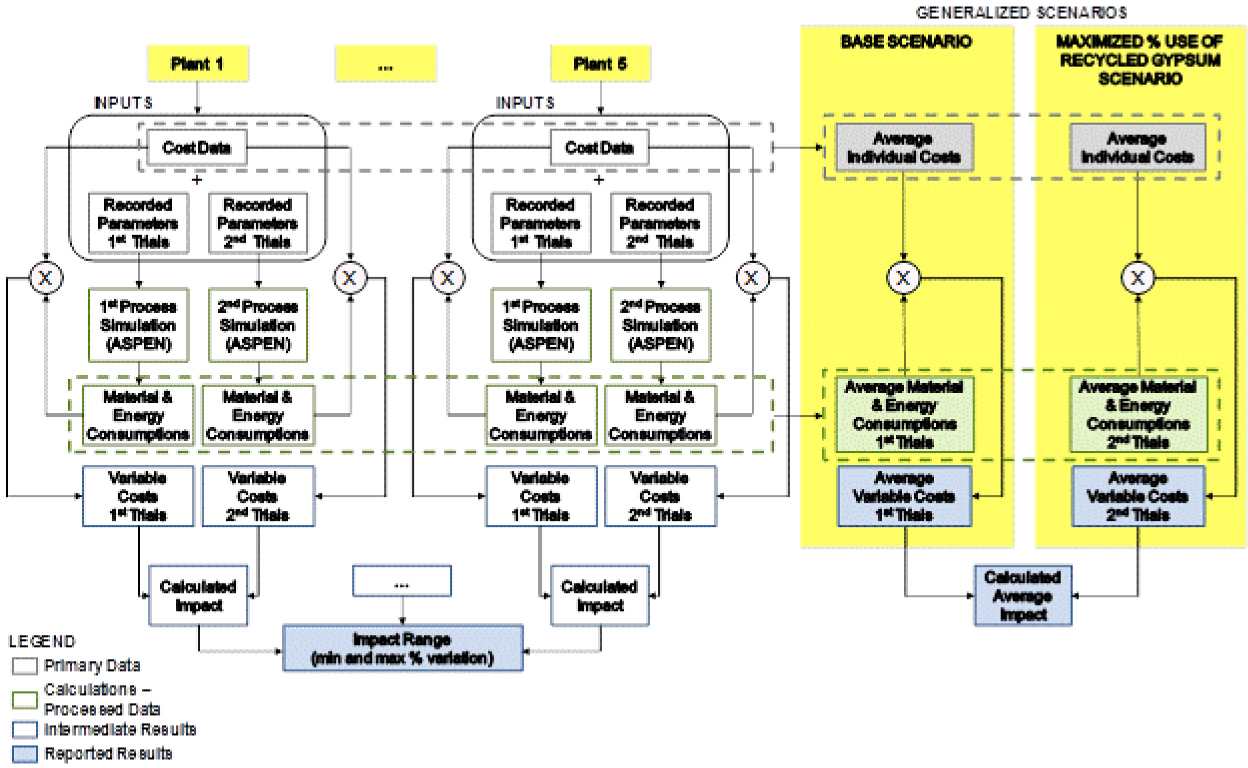

Figure 6-3 Calculation methodology of techno-economic impact assessment

The adoption of the above described methodology was preferred over the alternative of simply averaging the individual cost results of each plant because the results with the latter method are not always representative due to the considerable differences that were observed among the cost structures of the plants (i.e. deviations in the prices of cost parameters between plants). On the contrary, the chosen approach focuses on *the essential impact on the consumption of each cost element* (e.g. raw materials, water, energy etc.) caused by the use of recycled gypsum, *which is proportionally reflected on the respective average costs in the generalized scenarios*.

The values of average impact reported in the results section refer to the generalized scenarios, while the highest and lowest values show the respective impact range among the individual results of the plants.

The effect of recycled gypsum use on cost and energy consumption is also assessed for each of the two distinct main steps of the plasterboard manufacturing process; Stucco Production (includes raw material transportation –when applicable–, pre-processing and calcination) and Plasterboard Production (includes mixing of the stucco slurry, cutting, drying of plasterboard and internal recycling of production waste). 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.

6.4.1 Basic Working Assumptions

The calculations are based on the working assumptions summarized below:

1. Recycled gypsum is considered as one single stream regardless of the sources from which is derived (i.e. demolition, construction or production waste). However, differentiations in its composition (i.e. % derived from demolition etc.) are indirectly taken into account in the analysis, since they impact its basic properties (e.g. purity, main impurities, moisture content etc.) and pre-processing requirements.
2. The calculated cost / m^2 of plasterboard refers to the finished product excluding further downstream (packaging, distribution etc.) and labour costs.
3. The energy consumption and respective cost of the internal recycling of production waste, when applicable, is calculated based on the plasterboard waste output.
4. For the mass and energy balances the rate of conversion of the gypsum’s dihydrate content into hemihydrate in calcination is assumed 100%.
5. The energy consumption of raw material transportation – when applicable in the scope of study (see section 6.2.1) – is included in the calculation of thermal energy consumption of the Stucco Production stage.
6. With respect to fuel (composition, higher and lower heating value etc.), unless specific information is provided by the manufacturers, thermal energy calculations are based on data taken or adapted from literature [12-16] for the natural gas supplied in the four countries of location of the pilot plants.
7. The reduction of costs and energy per m^2 of net plasterboard production (i.e. excluding production rejects) is based on fixed percentages of wet and dry rejects generated in each of the

studied plants for both rounds of trials, even though actual data were recorded. This working assumption is set upon the fact that internal plasterboard waste generation does not present any consistent trend or correlation to the percentage use of recycled gypsum in the collected data. However, the assumed percentages are values adapted from the actual provided information (i.e. average percentage of rejects that occurred in each plant during the two trials).

6.5 Results and Discussion

6.5.1 Levels of Recycled Gypsum Re-incorporation Achieved

The use of recycled gypsum in the 1st round of trials ranges between 5-18% and it is increased up to 20-30% in the 2nd round of trials. This translates to 10,9% and 25,2% average re-incorporation for the generalized Base Scenario and Maximized % Use of Recycled Gypsum Scenario respectively. Two out of the five pilot plants have reported to reach the maximum target of 30%, but managed to stabilize the process at this re-incorporation rate only for a brief time period (~2 to 3 hours). The detailed results in regard to the percentage use of recycled gypsum in the two rounds of trials are shown in Table 6-1.

Table 6-1 Recycled gypsum re-incorporation rate in the two rounds of trials

	Use of Recycled Gypsum [% w/w in feedstock on a wet basis]					
	Plant 1	**Plant 2**	**Plant 3**	**Plant 4**	**Plant 5**	**Generalized Scenarios (Average)**
Trial 1	5%	8,9%	10%	10-15%	18%	**10,9%**
Trial 2	25,6%	19,9%	**30%**	25-**30%**	23%	**25,2%**

6.5.2 Impact on Variable Plasterboard Manufacturing Costs

Within the scope of the present study, 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 studied are natural gypsum, FGD or a mix of both. Fuel is mainly natural gas, however in some cases also waste fuel is partly used as supplement.

6.5.2.1 Variable Cost Structure

The distribution of variable costs of plasterboard manufacturing for the two generalized scenarios under study is shown in Figure 6-4. 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 total cost of both scenarios.

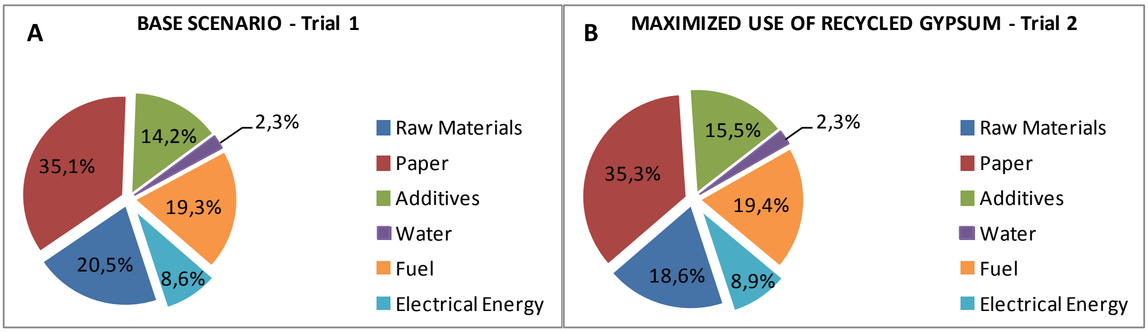

Figure 6-4 Variable plasterboard manufacturing cost structure

Figure 6-5 further focuses on the particular structure of material costs; paper accounts for 50,3% and 50,9% of material costs, raw materials for 29,3% and 26,8% and additives for 20,4% and 22,3% in Trial 1 and Trial 2 respectively.

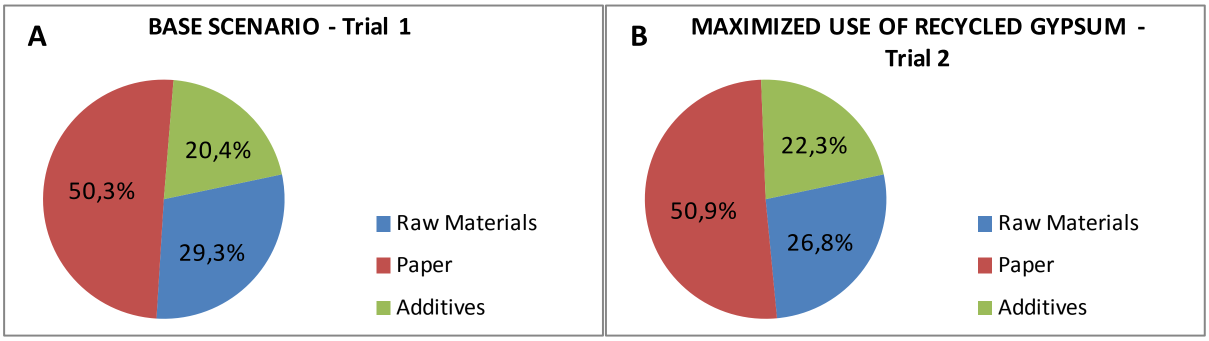

Figure 6-5 Materials' cost structure of plasterboard manufacturing

It should be clarified that the apparent –though small– impact on the % cost proportion of paper is due to resulting variations in the costs of the remaining elements and not to changes in the absolute 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. Nonetheless, paper is included in the study in order to highlight its high percentage in the cost structure, which indicates high sensitivity of the total variable plasterboard cost to paper cost (i.e. facing paper market prices).

Based on Figures 6-4 and 6-5, the key impact observed on the cost structure as a result of the increased incorporation of recycled gypsum into the process (2nd compared to 1st round of trials) is a shift of % cost proportion from raw materials to additives and, to a lesser extent, electrical energy.

6.5.2.2 Average Variable Costs

The impact on variable costs caused by the increased incorporation of recycled gypsum into the process for the two generalized scenarios is shown in Figure 6-6, according to which, the re-incorporation of recycled gypsum up to a feasible maximum causes an average 0,6% reduction 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 the previous section is more clearly reflected in the cost analysis of Figure 6-6; the evident considerable decrease of raw materials' cost (-9,5%) 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%), followed by electrical energy (2,9%). With regard to the remaining individual cost elements, water is marginally raised by 0,3%. In addition to raw materials, a slight drop of -0,2% is also shown in fuel cost.

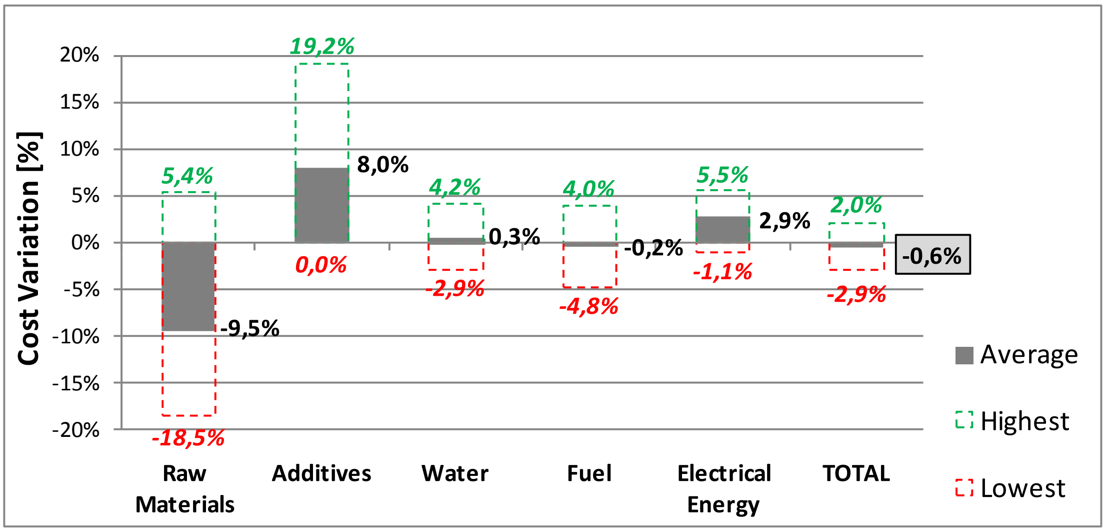

Figure 6-6 Average impact and range of impact of recycled gypsum use maximization on variable costs of plasterboard manufacturing

The significant decrease of raw materials' cost is due to the considerably lower prices of recycled gypsum compared to conventional gypsum market prices, whereas the fluctuations in the remaining variable costs relate to the quality and properties of recycled gypsum in conjunction with the process adaptations implemented. As already mentioned, the introduction or increase of recycled gypsum usage in the process alters a series of properties of the so far standard used feedstock/feedstock mix (e.g. particle size distribution, moisture content, purity, TOC, presence of impurities/contaminants etc.), which essentially determine the technical process characteristics that must be adapted in order to mitigate or overcome the resulting implications while maintaining the desirable product quality. The potential impacts of recycled gypsum use on key manufacturing parameters and the consequent direct or indirect effects on process costs are described in detail in Chapter 4.

Figure 6-6 also illustrates the range of impact caused by the maximization of recycled gypsum use in the five pilot plants. The observed wide range of impact (highest and lowest % cost variation) and the apparent conflicting trends in almost all the cost elements that range from positive to negative effects clearly indicate dependence of the results from the process characteristics (see Section 6.1.3). The 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. The levels of impact on total plasterboard cost also 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 more or less differ among the five plants.

The raw materials' cost decreases on average for the five plants by ca. 9.5%, despite the broad variation of this variable (minimum -18,5%, maximum 5,4%); in the 2nd round of trials the raw material cost is reduced in four out of the five plants.

A clearer trend appears in the cost of additives. In the 2nd trials additives consumption is higher in three out of the five plants. This cost increasing trend, that results in an average increase of 8%, is considered rather expected; as the use of a certain feedstock component increases – in this case recycled gypsum –, the feedstock mix quality changes and the properties of the stucco slurry will 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.

The net average effect on water cost for the generalized scenarios is a slight increase of 0,3%, but ranges from -2,9% to 4,2% among the plants, being reduced in three out of the five cases. Potential impact on water demand has already been described in Section 4.2.5. In summary, possible explanations for the large range of impact on water cost and 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 lower purity than conventional feedstock based on the analyses of the feedstock samples of the trials (see Table 5-11). 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 91,23% to 90,4% in the generalized scenarios, in two plants the mix's purity is slightly higher in the 2nd 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; longer time is needed for the complete calcination of coarse compared to finer particles. Residual humidity of the recycled gypsum may also influence the calcination of the mix. This affects the phase % composition in stucco (hemihydrate, unreacted dihydrate, potential presence of anhydrite) and even though the impact can be minimized by thorough calcination temperature conditions control and sieving, the net effect on stoichiometric water demand can be different for each plant, depending on the standard feedstock and process characteristics. It should be noted that anhydrite may be sometimes originally present in conventional feedstock as an impurity.
- Changes in the particle size distribution of stucco also affect the excess water demand in the slurry mixer. This impact can also differ among the studied plants depending on the type of standard feedstock used (i.e. natural and/or FGD) and the implemented process modifications (e.g. by adjusting the additives).
- The increased TOC (paper and fibres) in feedstock caused by the high incorporation of RG negatively affects the fluidity of the slurry and increases the excess water demand. The impact

can be mitigated by the use of appropriate additives, but the net individual effect can be, again, different in each plant.

The impact on fuel and electrical energy consumption and cost is further analyzed in Section 6.5.3.

As already mentioned, the dependence of the results from individual process characteristics in conjunction with the relatively small number of plants under study limits the accuracy and raises the uncertainty margin of the generalized average results shown in Figure 6-6, especially those referring to fuel and water that show minimal cost variations on average. However, in any case the results undoubtedly indicate that recycled gypsum usage in relation to its properties directly or indirectly affects process costs.

Moreover, despite the uncertainties and the inconsistencies in the trends of individual cost elements, the results for the range of impact clearly show that all manufacturers managed to minimize the impact on total plasterboard cost by appropriately adapting their processes, regardless of the existing process-specific differentiations. Based on the present study, it can therefore be concluded that the net average impact of the maximized use of recycled gypsum on the total variable manufacturing cost of plasterboard is practically negligible, *given its current market prices and quality*; essentially, the average cost remains almost invariable in both trials. Based on the analysis of Chapter 4 and the consolidated answers of the manufacturers to the re-incorporation questionnaires, it could be also safe to conclude that the highest financial benefit could be achieved if the quality of the recycled material is further improved to being as similar as possible to the conventional feedstock used in each case.

6.5.2.3 Variable Costs per Process Stage

The impacts identified in the study of variable costs of the process can be further analyzed in regard to its two distinct steps; Stucco Production and Plasterboard Production. Figure 6-7 shows the cost structure per process stage for the two generalized scenarios. The Plasterboard Production stage accounts for the higher share of plasterboard manufacturing cost (around 70% in both generalized scenarios). The respective value ranges for the cost shares per process stage among the five pilot plants are shown in Table 6-2.

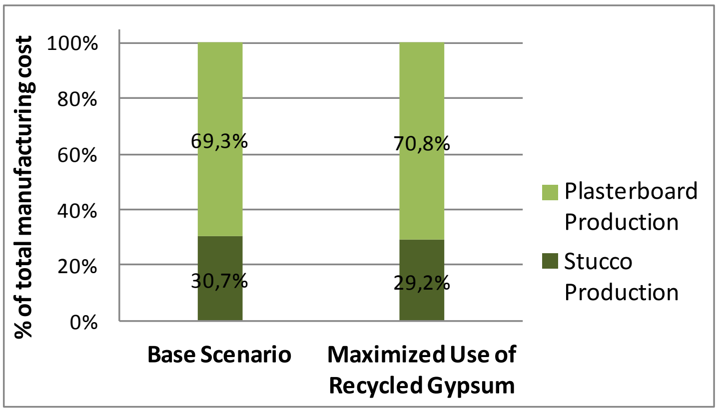

Figure 6-7 Cost structure of plasterboard manufacturing per process stage

Table 6-2 Cost structure of plasterboard manufacturing per process stage in the two rounds of trials

Stage	Share in total cost			
	BASE SCENARIO		MAXIMIZED USE OF RECYCLED GYPSUM	
	Value Range	Average Value (generalized scenario)	Value Range	Average Value (generalized scenario)
Stucco Production	29,6 - 32,6%	**30,7%**	27,9 - 30,8%	**29,2%**
Plasterboard Production	67,4 - 70,4%	**69,3%**	69,2 - 72,1%	**70,8%**

Given that the average cost of plasterboard remains practically invariable in both scenarios, the apparent 1,5% cost shift from the Stucco Production to the Plasterboard Production stage (Figure 6-7) essentially indicates a decrease in the cost of Stucco Production, at the expense, however, of Plasterboard Production cost. A clearer insight in this respect is illustrated in the related charts for each production stage presented below.

Detailed results regarding the impact on variable costs of the Stucco Production Stage which consist of raw materials, fuel and electricity are illustrated in Figures 6-8 and 6-9.

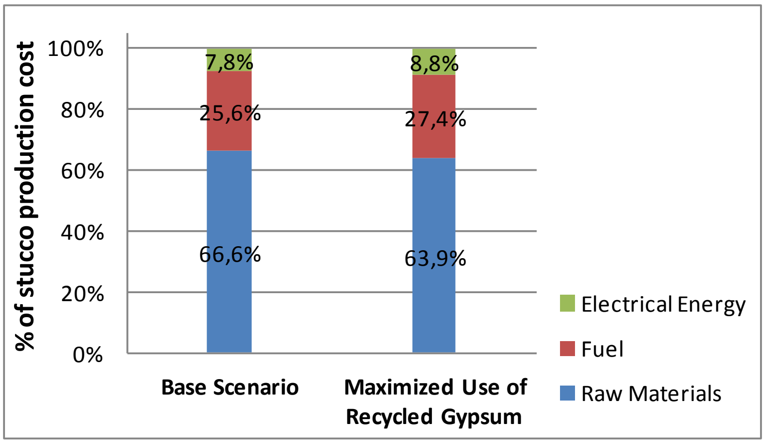

Figure 6-8 Impact of recycled gypsum use maximization on variable cost structure of Stucco Production stage

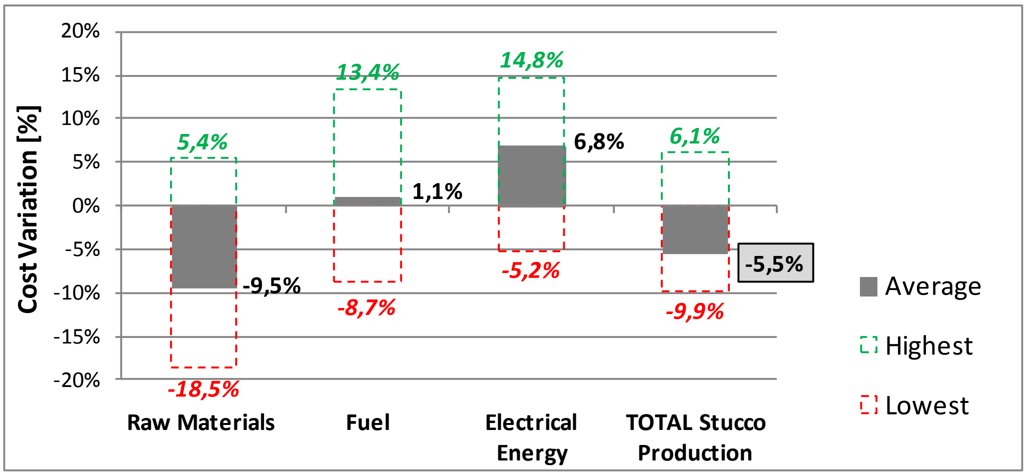

Figure 6-9 Impact and range of impact of recycled gypsum use maximization on variable costs of Stucco Production stage

As shown in Figure 6-9, the average cost of Stucco Production is reduced by 5,5% in the Maximized Use of Recycled Gypsum Scenario compared to the Base Scenario. This rather notable decrease is again due to the drop of raw materials' cost; due to the high sensitivity of Stucco Production cost to raw materials' cost (as seen in the cost structures of Figure 6-8) the 9,5% reduction of the latter overweighs the cost increases in energy (fuel 1,1% and electricity 6,8%) and determines the overall impact.

The reasons for the apparent discrepancies in the range of impact in Figure 6-9 have been discussed in the previous section. In this scope, the results show that 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 a small average increase of 1,1% within a wide range of impact, while electricity cost is increased rather significantly, but also varies widely.

The corresponding results for the variable costs of the Plasterboard Production Stage are presented in Figures 6-10 and 6-11.

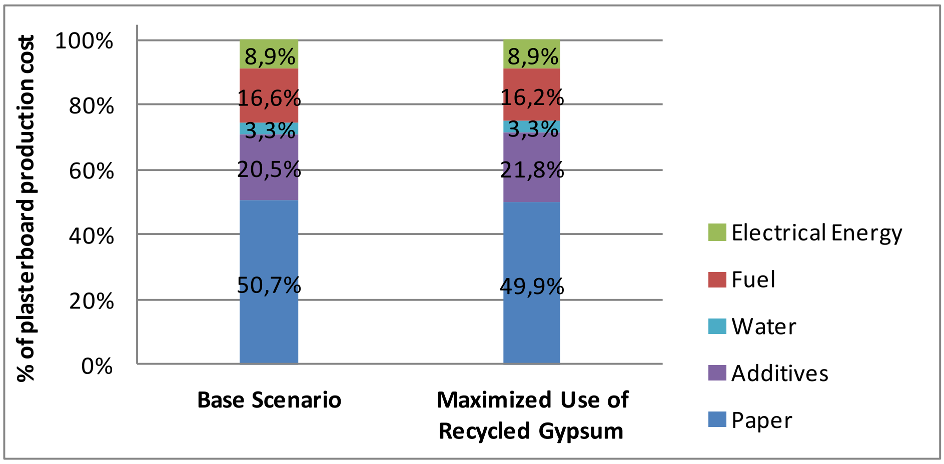

Figure 6-10 Impact of recycled gypsum use maximization on variable cost structure of Plasterboard Production stage

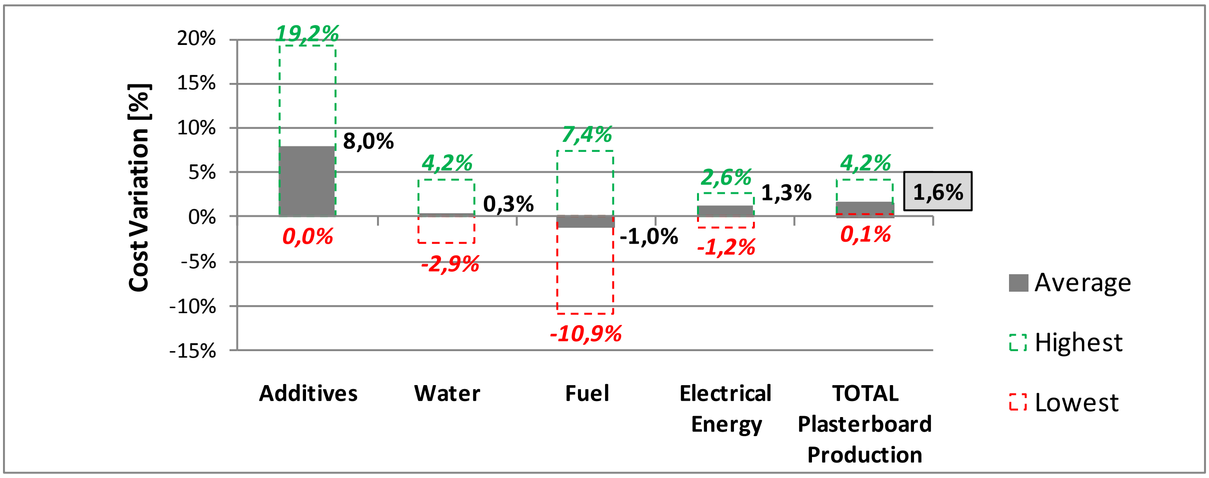

Figure 6-11 Impact (A) and range of impact (B) of recycled gypsum use maximization on variable costs of Plasterboard Production stage

The cost structure (Figure 6-10) consists of paper, chemical additives, fuel, electrical energy and water. Apart from paper which is –as already explained– excluded from the impact analysis, the main costs are additives (20,5% and 21,8% for the 1st and 2nd round of trials respectively), fuel (16,6% and 16,1%) and electricity (8,9% in both trials).

The average total cost for the Plasterboard Production stage (Figure 6-11) appears increased by 1,6% in the Maximized Use of Recycled Gypsum Scenario compared to the Base Scenario. The increase in this case mainly arises from the 8% rise of additives' cost to which total cost shows the highest sensitivity (see Figure 6-10), 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% (Figure 6-11). The effects on additives and water have already been discussed. Energy consumption issues, which directly relate to energy cost, are analyzed in the following section.

In summary, the principal impact of the maximization of recycled gypsum incorporation in respect to the two main steps of the manufacturing process is an average 5,5% decrease in the cost of Stucco Production stage which fully compensates the respective 1,6% cost increase in the Plasterboard Production stage, even though the latter is considerably more costly. This results in the 0,6% average decrease of total variable cost of plasterboard manufacturing for the two generalized scenarios.

6.5.3 Impact on Energy Consumption of Plasterboard Manufacturing

Energy consumption is related to CO_2 abatement costs, which are not included in the present techno-economic assessment. For this reason, the study of the impact on the energy consumption of the process is considered of particular interest and it is thus separately analyzed in this section.

The % distribution of energy consumption of the plasterboard manufacturing process for the two generalized scenarios is shown in Figure 6-12. Thermal energy accounts for the largest part of the process' energy demand (around 89%), and the distribution does not appear significantly affected by the use of recycled gypsum. The respective energy distribution ranges among the plants are shown in Table 6-3.

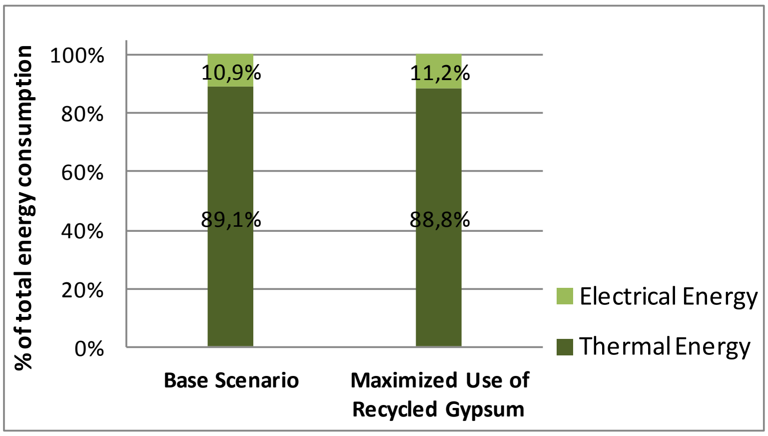

Figure 6-12 Distribution of energy consumption of the plasterboard manufacturing process for the two generalized scenarios

Table 6-3 Distribution of energy consumption in the two rounds of trials

Element	Share in total energy consumption			
	BASE SCENARIO		MAXIMIZED USE OF RECYCLED GYPSUM	
	Value Range	Average Value (generalized scenario)	Value Range	Average Value (generalized scenario)
Thermal Energy	77,5 - 95,3%	**89,1%**	76,5 - 95,3%	**88,8%**
Electrical Energy	4,7 - 22,5%	**10,9%**	4,7 – 23,5%	**11,2%**

The energy consumption per stage of the manufacturing process in the two generalized scenarios is illustrated in Figure 6-13. The process step of Plasterboard Production has considerably higher energy demand than Stucco Production, accounting for ~60% of the energy consumed in total. As observed here, the increased use of recycled gypsum appears to have caused a shift from the Plasterboard Production to the Stucco Production stage on both thermal and electrical energy % distribution.

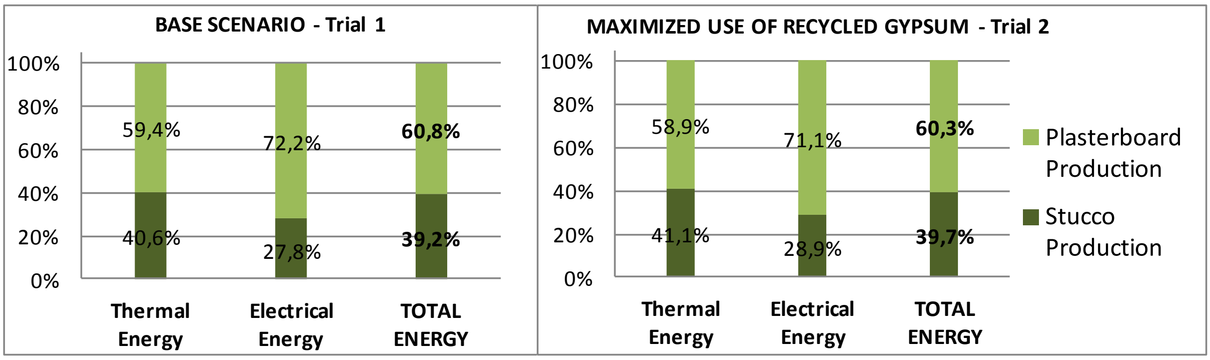

Figure 6-13 Distribution of energy consumption per process stage for the two generalized scenarios

Figure 6-14A shows the average energy consumption results for the two generalized scenarios. The primary impact observed is a 2,9% increase of electricity consumption, which, given the low share of electrical energy in the total energy demand of the process (Figure 6-12), results in practically negligible net effect on total energy; the calculated energy consumed in plasterboard manufacturing is ~5,5 KWh/m^2 on average for both scenarios.

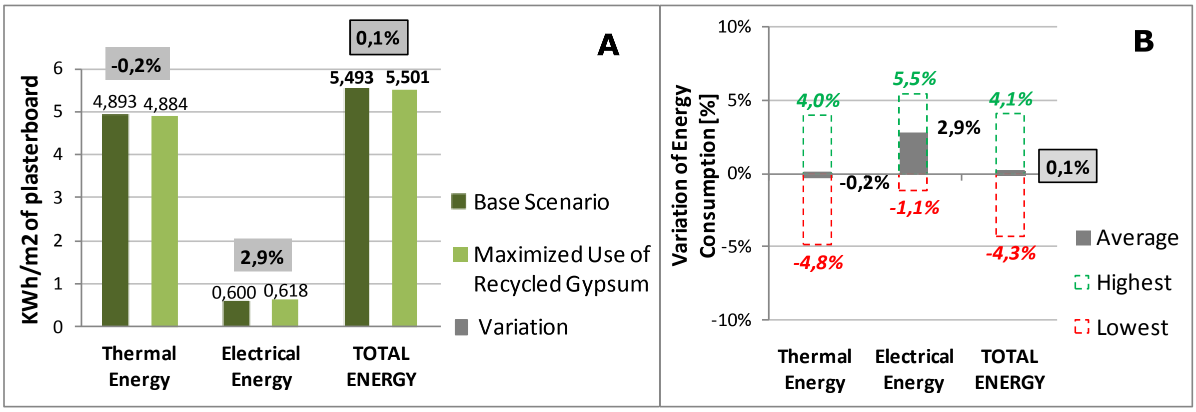

Figure 6-14 Impact of recycled gypsum use maximization on average energy consumption of plasterboard manufacturing process (A) and respective range of impact in the five plants (B)

As expected, the same ranges of impact and inconsistent trends identified in the cost assessment concerning energy appear in Figure 6-14B. As opposed to the average calculated impact, here the results show that the maximization of recycled gypsum usage has more notable negative or positive effects on the energy consumption among the five individual processes.

The net effect on energy consumption results from the combined impact on a series of factors. In this context, the study of the impact of recycled gypsum use per stage of the process gives a clearer picture.

The results for the Stucco Production Stage are illustrated in Figure 6-15. It is observed that both thermal and electrical energy demand of Stucco Production are increased by 1,1% and 6,8% respectively compared to the Base Scenario, resulting in a 1,5% increase of the energy consumed in total (Figure 6-15A). The average energy consumption for the scenario of Maximized Use of Recycled Gypsum is 2,184 KWh/m^2.

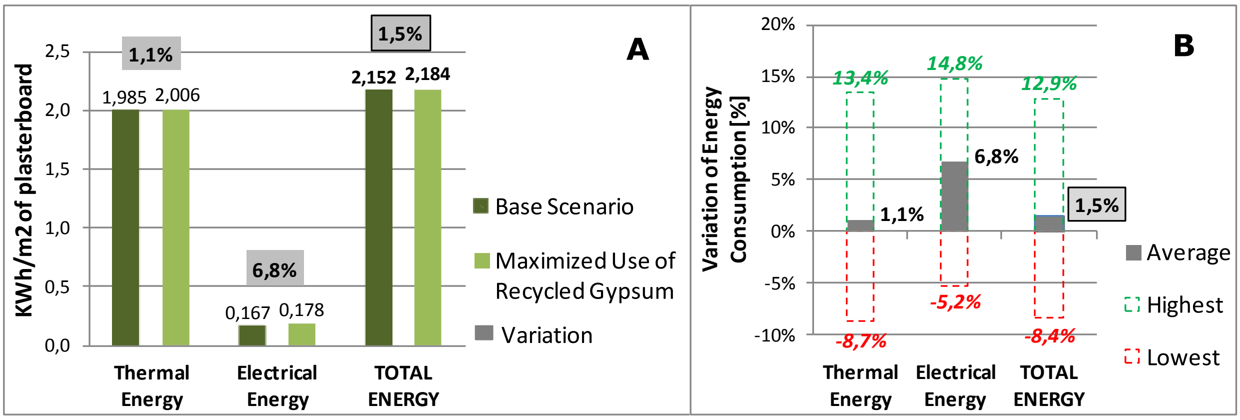

Figure 6-15 Impact of recycled gypsum use maximization on average energy consumption of the Stucco Production stage (A) and respective range of impact in the five plants (B)

Stucco Production requires thermal energy for the drying and calcination of gypsum raw materials. According to the calculations the related fuel consumption decreased in two out of the five plants in the 2nd round of trials. The discrepancies and the wide range of the impact on thermal energy consumption among the plants (from -8,7% to 13,4% according to Figure 6-15B) could therefore be attributed to the effect on the moisture content and purity of each feedstock mix as a result of the increased incorporation of recycled gypsum. The moisture of the recycled material used in the 2nd trials is a lot higher than that of conventional feedstock in four of the cases studied, so it negatively affects the moisture of the mix and the fuel demand for drying. On the other hand, due to its typically lower levels of purity, recycled gypsum mostly reduces the purity of the mix and the respective theoretical fuel demand of calcination and the negative effect on drying energy may be compensated to a certain extent. In practice however, the thermal energy consumed in calcination may be also affected by possible changes in the rate of conversion and the phase composition of stucco and therefore, the overall net effect on the thermal energy consumption varies depending on the individual characteristics of each plant.

The impact on electrical energy relates to changes in the process mass balance (i.e. feedstock/stucco ratio, bulk density of materials handled etc.) and to adjustments in the load and speed of the machinery in order to maintain a given production rate. As shown in Figure 6-15B, the individual effects on electricity consumption also vary significantly from -5,2% to 14,8%, but the trend is mostly increasing; electricity consumption is higher in the 2nd round of trials in four of the studied cases. This can be attributed to the overloading of the recycled material feeding systems (see Section 4.3.2) and to the impact on the feed/stucco ratio, which increased in four of the plants mainly due to the raised moisture of feedstock. Higher feed/stucco ratio means that higher masses of materials are handled in the Stucco Production Stage, which translates in increased electricity consumption. On the other hand, some electrical energy savings compared to the Base Scenario are achieved in the cases that include primary crushing of natural gypsum due to its part replacement by recycled gypsum powder. It should be noted that even though the observed 6,8% increase of electricity consumption seems rather high, it does not have such considerable effect on total energy given the low % share of electrical energy in the total energy demand of the process (see Figure 6-12).

The results for the energy analysis for the Plasterboard Production Stage are shown in Figure 6-16.

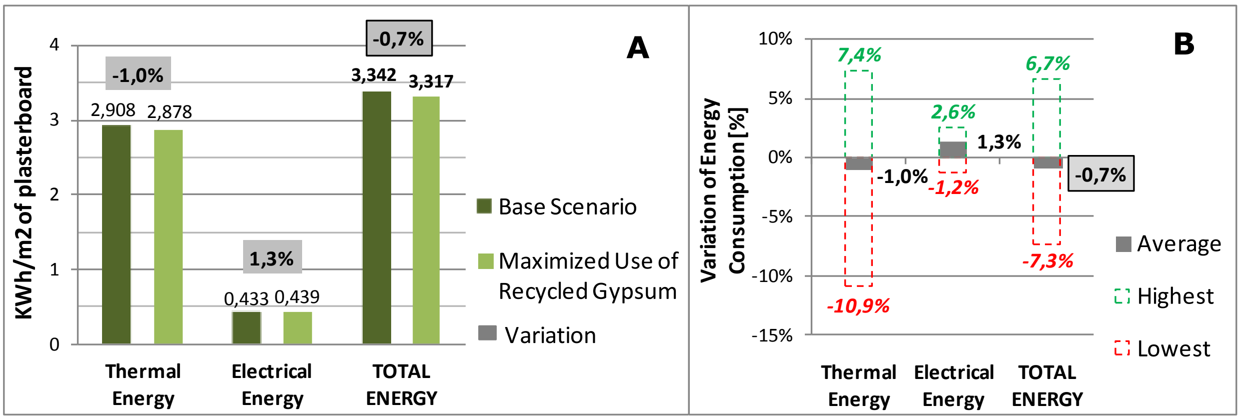

Figure 6-16 Impact of recycled gypsum use maximization on average energy consumption of the Plasterboard Production stage (A) and respective range of impact in the five plants (B)

Thermal energy consumption shows an average 1% decrease that causes a marginally positive impact (i.e. 0,7% drop) on total energy for the generalized scenarios. The individual impact on thermal energy ranges from -10,9% to 7,4% and is determinant of the also wide range of impact on energy in total. Electrical energy on the other hand shows a small increase on average within a small impact range.

In the Plasterboard Production stage thermal energy reflects fuel demand in the dryer and is directly related to the amount of excess water in the stucco slurry that has to be driven off from the board's core. Therefore, the impact on excess water demand due to the maximization of recycled gypsum inclusion in plasterboard determines the respective impact on thermal energy consumption at this process stage. In this context, the extent and the inconsistencies in the impact range on thermal energy among the plants can be potentially explained by what has already been discussed regarding excess water in Section 6.5.2.2. Thermal energy is decreased in two of the studied plants in the 2nd round of trials.

Electrical energy consumption relates to changes caused in the load and speed of the board line. Given that the density of plasterboards is not significantly affected based on the results of the product samples analyses (see Section 5.4.3), the observed impact can be mainly attributed to adjustments of the line speed. It is worth mentioning that according to the calculations, electricity consumption of Plasterboard Production remains practically invariable in three of the five plants in the 2nd round of trials.

In all cases, the energy analysis shows that the maximized incorporation of recycled gypsum results in a small drop of thermal energy consumption that fully compensates the relative increase in electrical energy. In terms of the two main steps of the process, small negative effect (i.e. increase) is observed in the total energy consumption of Stucco Production, which is however overweighed by a respective decrease in the total energy of Plasterboard Production. In any case, the net resulting impact on the average energy consumption per m^2 in total for the complete plasterboard manufacturing process is negligible.

6.5.4 Sensitivity Analysis

6.5.4.1 Uncertainty Margin

The quantification and recording of some process parameters may have been sometimes difficult given the time limitations (i.e. the relatively short duration) of the trials, and the accuracy of the input data of the techno-economic assessment could be thus compromised. Moreover, the recorded parameters depend –as already mentioned– on the specific set of adjustments made in the 2nd round of trials according to the particularities of each process; different adjustments could lead to different outcomes. In order to estimate the corresponding uncertainty margin of the results, a sensitivity analysis is performed through testing the average calculated impact for the generalized scenarios by varying the key input parameters about which it is considered that there may be uncertainty. These are specifically all the energy and certain material consumption values (additives, water and paper) provided in the data templates. Raw material consumptions are not included in the sensitivity analysis variables, since the calculated impact should always refer to the specific levels of re-incorporation achieved.

As expected, the results are highly sensitive to the accuracy of the input data; by varying the inputs ±5% the average impact on total variable plasterboard manufacturing cost ranges from -4,6% to 3,8%. The respective impact on energy consumption shows greater influence, ranging from -9,1% to 10,4%.

Therefore, within the boundaries of uncertainty in this assessment, the calculated average 0,6% reduction of total variable plasterboard cost (see Figure 6-6) is too small to conclude a –however low, yet– categorical benefit of increasing the content of recycled gypsum up to ca. 30% in Type A plasterboard production. Accordingly, neither the marginal average impact of 0,1% on total energy consumption (Figure 6-14) can be considered conclusive. In reality, potential savings or losses will probably lie somewhere in between the estimated uncertainty thresholds.

6.5.4.2 Impact Assessment in Relation to Price Increases of Variable Cost Elements

Aside from the uncertainties, according to the present assessment recycled gypsum incorporation in the plasterboard manufacturing process at high levels appears economically favorable compared to the generalized Base Scenario.

In the framework of a threshold analysis, the % price increases of the individual variable cost elements at which the total plasterboard cost per m^2 at the Maximized Recycled Gypsum Use Scenario equals the respective cost of the Base Scenario can be defined as breakeven points (BEPs). These are essentially the maximum market price increases that the manufacturers can “afford” to fully redeem the benefit gained if using recycled gypsum at the maximum feasible levels becomes standard practice. The calculated BEPs are given in Table 6-4.

Table 6-4 Breakeven points of individual variable cost elements

Cost Element	BEP (Maximum % Market Price Increase)
Conventional Raw Materials	3,3%
Paper	1,7%
Additives	3,8%
Water	26,6%
Fuel	3,0%
Electrical Energy	6,7%

A single factor sensitivity analysis is performed to investigate the extent to which the net % impact on total plasterboard cost is influenced by potential increases 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. The results are illustrated in Figure 6-17 (0% increase represents current impact).

It is observed that the % impact on the average total variable plasterboard manufacturing cost as a result of the maximized use of recycled gypsum is sensitive to the prices of conventional raw materials and additives (Figure 6-17A and B). This is of course expected, considering the significant shares of these two elements in the cost structure (see Figure 6-4) and given the fact that they result to be the most affected by the use of recycled gypsum (Figure 6-6).

More specifically, increases in the prices of conventional raw materials raise the positive impact on plasterboard cost (i.e. decrease). Figure 6-17A shows that a price increase of 30% doubles the achieved benefit, from currently -0,6% to ~-1,2%. Stucco Production cost respectively shows greater decrease from -5,5% to -6,4%.

On the contrary, the use of recycled gypsum is not favored by additives’ price increases, which cause greater negative effect (i.e. increase) on the cost of the Plasterboard Production stage and thus reduce the overall cost benefit achieved by the high re-incorporation of recycled gypsum; e.g. 10% rise of prices diminishes the benefit from -0,6% to ~-0,45%. 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 6-17B).

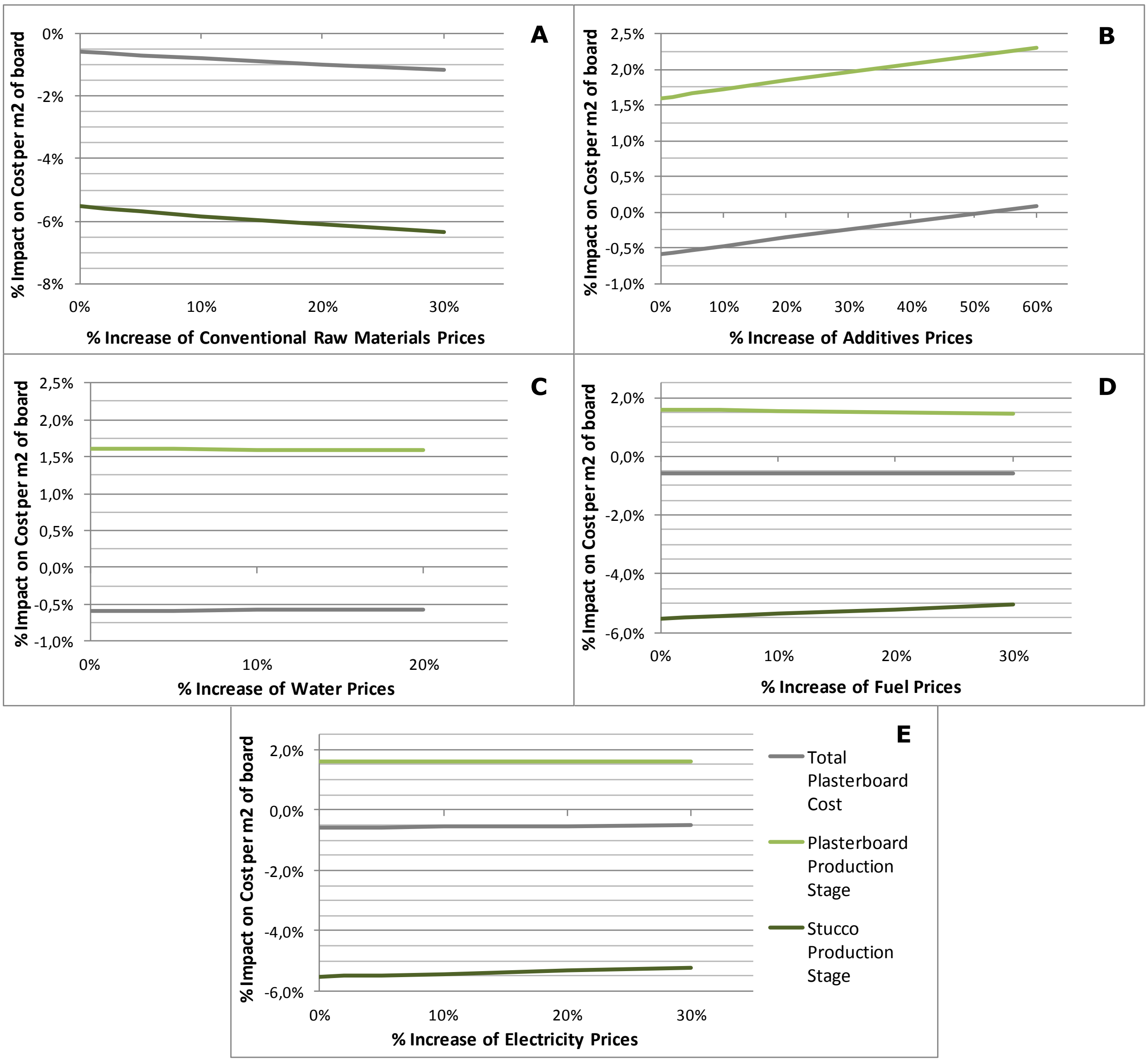

Figure 6-17 Results of sensitivity analysis to market price increases of individual cost elements

Figure 6-18 illustrates the combined influence of these two main sensitivity factors of total plasterboard cost. It basically 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 use of recycled gypsum. As opposed to that, highly increased additives prices at (close to) current conventional feedstock price rates tend to shrink the cost savings gained.

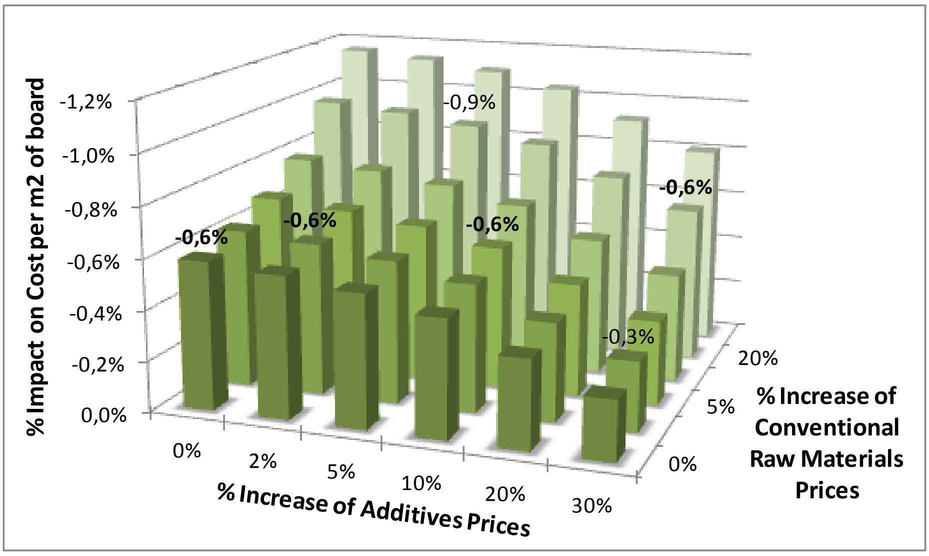

Figure 6-18 Impact of price increases of conventional gypsum and additives on the cost of plasterboard with high recycled gypsum content

As expected, the impact on total plasterboard cost appears non-sensitive to water price variations (Figure 6-17C), given the low level of effect of recycled gypsum use on water (Figure 6-6) and the low share of water in the cost structure (Figure 6-4).

With a <5% influence from price variations of up to 30% it is also considered non-sensitive to fuel prices, even though the cost savings achieved for the Stucco Production Stage are reduced as fuel prices rise (Figure 6-17D). This is mainly attributed to the negligible net impact of recycled gypsum use maximization on the cost of fuel (see Figure 6-6).

Finally, the impact shows little influence to electricity price variations; 30% rise in prices causes the savings in plasterboard cost to shrink from -0,6% to -0,5%, due to the respective effect on Stucco Production cost (Figure 6-17E).

It should be noted that the saving on total plasterboard cost shows little sensitivity to price increases *in terms of absolute value*, since it is originally low. However, the trends appearing in Figure 6-17 are considered indicative of potentially higher influences, given the relatively wide uncertainty margin of the average impact levels.

In summary, the key outcome of the sensitivity analysis is that the use of recycled gypsum at high levels is favorable to price increases of conventional raw materials, but the benefits gained are negatively influenced and may even be fully dissipated by increases in the prices of additives. The impact on total plasterboard cost is not considered to be particularly sensitive to the prices of the remaining three cost elements.

7. Conclusions

Overall, the GtoG trials have shown, that it is indeed possible for the plasterboard manufacturing plants to move towards 30% incorporation rate of recycled gypsum, which was the target of this project.

Based on the outcome of the production trials, higher level re-incorporation of recycled gypsum into plasterboard manufacturing has proved feasible in practice; all the plants achieved to increase considerably the inclusion of recycled gypsum in the process. The recycled material used in the production trials generally conformed to proposed specification limits. Within the framework of the limited duration of the trials, the achieved % inclusion rate and the characteristics of the recycled material used in each case, the problems and difficulties encountered were successfully overcome with appropriate, non-permanent process adjustments. Moreover, based on the analyses of product samples, the use of recycled gypsum does not noticeably affect the basic performance characteristics of the plasterboards and all samples received for analysis could be classified as 12,5 mm Type A plasterboards according to EN-520 Standard.

The number of sample cases (five plants) constrains the level of independence of the results from the process characteristics, which were not identical in terms of the feedstock/feedstock mix used, the raw material pre-processing stages, the types and set-up of industrial equipment employed etc. Furthermore, potential differences also exist in the process adjustments and modifications made by each manufacturer as a result of the higher recycled gypsum re-incorporation at the 2nd round of trials. As a consequence, there is some “in-homogeneity” in the original collected datasets, which results in inconsistent impact trends on individual parameters among the five separate cases studied, thus limiting the accuracy and increasing the uncertainty range of the generalized average results of the techno-economic assessment. A larger sample size would considerably improve the quality of the average results.

It is concluded from the techno-economic assessment carried out in the frame of the present study that the net average impact of the maximized use of recycled gypsum on the total variable manufacturing cost and energy consumption per m^2 of plasterboard is practically negligible, given its current market prices and quality. Specifically, the key impact observed is a marginal 0,6% total cost reduction arising from a considerable decrease of raw materials’ cost that fully compensates for the cost increases caused to other process parameters, predominantly additives. High level usage of recycled material necessitates slight adaptations of the plasterboard recipe and of certain process parameters, which level the potential cost benefits mainly due to the requirement of higher amounts of relatively costly chemical additives. In any case, the assessed effects on individual cost elements undoubtedly confirm that recycled gypsum usage directly or indirectly impacts process costs. In respect to the two distinct steps of the manufacturing process, recycled gypsum incorporation leads to a decrease in the cost of Stucco Production stage which overweighs the respective cost increase in the Plasterboard Production stage. The energy analysis shows a negligible 0,1% increase of total energy consumption – indicative of the impact on CO_2 abatement costs – as the net effect of small variations caused in the thermal and electrical energy consumption of the process. However, within the (wide) boundaries of uncertainty of the assessment, the calculated impact is too small to conclude a measurable cost benefit when increasing the content of recycled gypsum ca. 30% in Type A plasterboard production. In reality, potential savings or losses lie in between the estimated uncertainty thresholds of the analysis performed within the frame of the current project.

Aside from the uncertainties, the main conclusion of the sensitivity analysis is that the use of recycled gypsum at high levels is favorable to potential market price increases of conventional raw materials. However the benefits gained are negatively influenced by increases in the prices of additives. Finally, the impact of re-incorporation on plasterboard cost is not considered particularly sensitive to the prices of water, fuel and electricity.

The results of the techno-economic analysis vary widely among the plants studied, showing relatively broad ranges of impact on individual parameters which indicate high dependence on process-specific characteristics and implemented adjustments' set. Nonetheless, the results obtained show that all the plants under study managed to appropriately adapt their processes to the high level use of recycled gypsum and practically minimize any potential process effects. The experience gained during the maximized re-incorporation trials is valuable and the strong will to adapt the production process to re-incorporate recycled gypsum in the feedstock is clearly outlined.

In summary, the work carried-out fulfilled the goal & objectives of Action B3. Overall, the GtoG trials:

- Proved that **re-incorporation (up to 30%) of recycled gypsum in Type A plasterboard manufacturing is feasible in practice**, even under the adverse conditions of non-permanent process adjustments. 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 fee for land-filling). Stronger economic and environmental benefits can arise in the future, when the necessary process modifications will be optimised and the recycled material quality will consistently rely with the quality specifications set by the GtoG project.
- Highlighted **potential production bottlenecks in terms of recipe modifications** (e.g. in additives) **and production process equipment** (e.g. storage, feeding conveyors, recycled gypsum pre-processing etc.) that may arise when the increased percentage becomes standard practice in the plasterboard manufacturing. The outcome of the production trials allows each of the manufacturers to develop plans for the relevant and necessary industrial adaptations, which are costly and require further trials and time.
- Proved in practice the full engagement of plasterboard manufacturers to develop recycling practices that will permit higher re-incorporation percentages in the future. For the first time, and in the frame of Action B3 of GtoG, the plasterboard manufacturing industry performed controlled and synchronized production trials in five different plants.

The overall findings and the collective knowledge-experience obtained by the manufacturers are promising and permit planning of future investigations even at higher re-incorporation percentages.

8. Recommendations and Future Steps

The conditions of the present research (five plants with different sources of conventional and recycled material and manufacturing practices) did not allow the assessment of the impact of specific recycled gypsum characteristics on the process parameters. However, the specifications of recycled gypsum and the consistency of its characteristics can be anticipated to play a critical role in maintaining the plasterboard quality (compliance with EN-520 Standard) with minimum process adaptations.

Due to the individualized procedures followed at each plant, GtoG cannot develop a generalised methodology, including standardized plant modifications, for the optimum/highest inclusion percentage of recycled gypsum in the plasterboard manufacturing process. Nonetheless, the experience acquired can provide important guidelines and thus contribute to setting or updating the framework for an EU quality specification for recycled gypsum. Recycling at higher levels may call for tighter specifications for recycled gypsum, since a material of fixed high quality would be desirable in order to minimize implications and adaptations of the process.

In this context, purity is reported as a potential restriction with regards to increasing the level of recycling to higher percentages. Locality plays an important role in the quality of the recycled material in this respect; the purity of recycled gypsum within a certain geographical area is highly possible to be similar with that of the plasterboard produced from nearby plants and this should be helpful for local recyclers to meet particular purity specifications. In other words, manufacturers are likely to receive post-consumer recycled gypsum originating from their own products. Further studies are needed to assess quantitatively the implications of recycled material purity.

The presence of silicones in the recycled material is considered to pose a measurable risk, especially depending on the type of board manufactured. The further investigation of the inclusion of such recycled material in the process and a related specification is thus recommended.

Residual paper content is also pinpointed as an important re-incorporation limiting factor. In fact, specifications on TOC should be kept particularly low, because in the long-term post-consumer recycled gypsum will originate from plasterboards with already high content of recycled material, thus continuously raising TOC levels. This would obligate manufacturers to change the feedstock pre-processing process which would translate in considerable capital cost investments in equipment. Developments in the recycling process should therefore focus on overcoming the current technical difficulties to completely remove paper fibres from the waste powder.

In respect to residual paper, a specification for the maximum acceptable size of paper pieces, as exists in the related British standard PAS 109 [17], is also considered required.

In order that re-incorporation at the project's target rate of 30% becomes standard practice, the recycled material volumes required for constant dosage supply need to be available and some investment for process upgrades (e.g. storage, feeding conveyors, recycled gypsum pre-processing set-up etc) from the manufacturers' part may be inevitable. The feasibility of continuous and systematic provision of the amount of recycled material necessary to meet production needs must be assessed by both recyclers and manufacturers.

In any case, as long as the incorporation of recycled gypsum in the manufacturing process is established at high levels on a constant basis or even further increased, the recycled gypsum specifications may have to be revised in the future; recyclers may have to seek and implement more sophisticated decontamination techniques and/or waste sorting methods and criteria for reclaim, as already suggested by the manufacturers, and minimize fluctuations in the quality of the recycled material.

The net impact of recycling is highly dependent on the “perimeter” of the analysis. The present work in the frame of Sub-Action B3 of GtoG Project constitutes a first attempt to record the important parameters of plasterboard manufacturing, in a strictly defined scope that aims to “isolate” and clearly identify the impact on the process within its limits. The recording of more than one data set during the 2nd round of trials (i.e. for gradually increasing percentages of recycled gypsum inclusion) would also provide a basis for parametric investigation of the impact on the process in relation to some basic characteristics of recycled gypsum (such as moisture and purity). This requires improvements of the recording methods and could be the object of further work.

Based on the conclusions of this report and the suggestions of the manufacturers, other proposed guidelines for future work could include the following:

- The results of the techno-economic assessment are limited by the short duration of running the production at the maximum level of re-incorporation achieved during the GtoG trials. Therefore, the impact of higher re-incorporation rates of recycled gypsum *on a constant basis* needs to be further assessed. More test productions would enrich the know-how on reincorporation issues and could eventually lead to the process up-grade investments required in order for maximum re-incorporation to become routine practice.
- In addition to standard Type A plasterboard, the use of recycled gypsum in the manufacturing of more technical board types and other gypsum-based products should be also investigated.
- Regarding the issue of constant sufficient supply of recycled gypsum to the plants, only estimates of the amount of recycled material that might become available at national/ EU level currently exist. A more precise mapping of sources (building types, location etc.) and quantitative estimation would be very helpful in future planning.

9. References

[1] Bundesverband der Gipsindustrie e.V. (Federal Association of Gypsum Industries), *The Gypsum Data Book*, 2006

[2] WRAP, *Life Cycle Assessment of Plasterboard*, Waste and Resources Action Programme, 2008

[3] Gypsum Association, *www.gypsum.org*

[4] EUROGYPSUM Environment and Raw Material Committee, *Factsheet on What Is Gypsum*, 2007

[5] Technical University of Madrid (UPM), *DA.1 Report Inventory of current practices,* GtoG LIFE+ PROGRAMME LIFE11 ENV/BE/001039, 2013

[6] The ATHENA Sustainable Materials Institute, *Life Cycle Analysis of Gypsum Board and Associated Finishing Products*, 1997

[7] Henkels P.J., *Gypsum Plasters and Wallboards,* In: Kogel J.E., Trivedi N., Barker, J.M., Krukowski S.T., *Industrial Minerals & Rocks – Commodities, Markets and Uses*, Society for Mining, Metallurgy and Exploration Inc., 7th edition, 2006, pp. 1143-1152

[8] New Zealand Institute of Chemistry, *Plaster and Plasterboard Production*, In: *Chemical Processes in New Zealand*, 2nd Edition, 1998

[9] Henkels P.J., Gaynor J.C., *Characterizing Synthetic Gypsum for Wallboard Manufacture*, American Chemical Society, 41 (2), 1996, pp. 569–574

[10] Henry Company, *Environmental, Health, & Safety Impact of Common Water Resistant Additive Technologies In Gypsum Wallboard Production*, 10th Global Gypsum Conference, 2010 *(Available at: http://us.henry.com/fileadmin/pdf/literature/EHS_Global_Gypsum_Conference.pdf)*

[11] Aspen Technology, Inc., Aspen Plus® Version 2006

[12] INGAS Integrated Project, *Report on gas composition range in Europe – DB0.1*, 2010 *(Available at: http://www.ingas-eu.org/publications.php]*

[13] ECN Phyllis 2 Database for Biomass and Waste (*https://www.ecn.nl/phyllis2/)*

[14] GasTerra, *http://www.gasterra.nl/en/kenniscentrum/wat-is-aardgas*

[15] Nationalgrid, *Natural Gas Safety Data Sheet*, January 2006 *(Available at: http://www.co-gassafety.co.uk/downloads/March%202010/National_Grid_Natural_Gas_Pre_Combustion.pdf)*

[16] Digest of UK Energy Statistics (DUKES) 2013, *Chapter 4 – Natural Gas*, (*Available at: https://www.gov.uk*)

[17] WRAP – BSI, PAS 109 :2013 *Specification for the production of reprocessed gypsum from waste plasterboard*

Appendix I

The questionnaire used for the recording of the directly observed practical impacts of the increased use of recycled material on the process during the 2nd round of production trials).

REINCORPORATION ISSUES AFTER SECOND TRIAL

Did you face any process related problem**s** during the 2nd round of trials optimizing up to 30%?	
Describe difficulties and/or problems that you encountered during the reincorporation production trial. Please list the cause/ reason **for EACH encountered problem** (e.g. for each process parameter that you had to adapt/control, recycled gypsum quality parameter, inability of equipment to cope with increased loads etc**.**	
Please describe the adaptations that were needed to your process in order to achieve the target recycled percentage	
Please list equipment modifications that will be needed if the increased reincorporation percentage becomes routine practice	
List of potential reincorporation issues - **Plaster production** - handling (P&PB) - quality of mixture with other gypsum (which gypsum kind) (P&PB) - moisture content of recycled gypsum (P&PB) - instability of process - others	
List of potential reincorporation issues - **Plasterboard production** - recycling in a part of production program (x% of total time), because of process issues (P&PB)) - instability of process - process compensation needed with costly chemicals (P&PB) - energy limitation (P&PB) - reducing speed of line - quality issue of finished products (P&PB) - others	
Did you overcome the problems: YES/NO	

Appendix II

For consistency reasons with other Actions of the GtoG Project the average energy consumption results are given *per tonne of plasterboard* in the following table. Some discrepancies that may appear compared to the corresponding results per m^2 are due to changes in the bulk densities of the materials handled caused by the changes in the feedstock mix (i.e. maximized incorporation of recycled gypsum).

Table AII-1 Average energy consumption per tonne of plasterboard for the two generalized scenarios

	Energy Consumption [KWh/t]	
	BASE SCENARIO	**MAXIMIZED USE OF RECYCLED GYPSUM**
THERMAL ENERGY		
Stucco Production	226,6	227,0
Plasterboard Production	333,1	325,8
TOTAL THERMAL	**559,7**	**552,8**
ELECTRICAL ENERGY		
Stucco Production	19,3	20,3
Plasterboard Production	50,6	49,9
TOTAL ELECTRICAL	**69,9**	**70,1**
TOTAL ENERGY		
Stucco Production	245,9	247,3
Plasterboard Production	383,6	375,6
TOTAL	**629,6**	**622,9**