

# Athens Journal of Sciences

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# Athens Journal of Sciences

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The current issue is the second of the tenth volume of the *Athens Journal of Sciences (AJS)*, published by [Natural & Formal Sciences Division](#) of ATINER.

Gregory T. Papanikos, President, ATINER.



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**22-25 July 2024, Athens, Greece**

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- Acceptance of Abstract: 4 Weeks after Submission
- Submission of Paper: **24 June 2023**

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## Identification of Greenish Soybean Seeds through Image Processing, under Different Types of Lighting

By Alcebiádes Fogaça de Souza Sobrinho<sup>\*</sup>, Roberto Alves Braga Junior<sup>±</sup>,  
Edvaldo Aparecido Amaral da Silva<sup>°</sup> & José Luís Contado<sup>•</sup>

*A high occurrence of greenish soybean seeds in crops is an issue, these types of seeds have low physiological quality, which can generate seedlings with anomalies, if destined for processing in industries, the presence of chlorophyll is undesirable, requiring additional processes for its removal. This work aimed to evaluate the differentiation of mature and greenish soybean seeds, illuminated with red laser, green laser, red LED, and fluorescent lamp, using image processing. Images of mature and greenish soybean seeds were captured at a resolution of 340x480 pixels, illuminated with red laser, green laser, red LED, and fluorescent lamp. Subsequently, the averages of the gray levels of each image were obtained in the red, green, blue channels and in images converted to grayscale 8-bit. The data were submitted to tests of variance after gray level for image classification. And a validation presented results of 97% of hits for red laser, 94% for fluorescent light and 93.5% for red LED, all in red channel.*

**Keywords:** seed classification, agricultural automation, soybean seed quality, computer vision

### Introduction

Soybean is one of the most important crops in the world, its grains are used both for protein food and for the production of vegetable oil (Hartman et al. 2020). The total cultivated area in the world during the 2018/2019 harvest was approximately 120 million hectares, with a total grain production of around 335 million tons (USDA 2020). And for soybean production, climate instability is an increasingly recurrent problem. Crop yields in general, including soybeans, are expected to decline due to climate stress factors that include drastic temperature fluctuations, drought, flooding and high salinity of water and soil (Li et al. 2017). High temperatures and water stress can lead to the occurrence of “green seeds” in soybean, which is characterized by the retention of chlorophyll in mature seeds (Teixeira et al. 2016). At seed maturation, the occurrence of abiotic and biotic stresses, including nematode parasitism, can result in premature death of soybean plants, resulting in the production of greenish seeds (França-Neto et al. 2012). In Brazil, where more than 60% of soy production is concentrated in tropical regions, the occurrence of high levels of green seeds is becoming an increasingly frequent problem for producers (Cicero et al. 2009). In the province of Ontario, Canada,

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due to the scarcity of rain, coupled with the extremely hot weather, resulted in samples collected containing 15% greenish soybeans in most fields of the 2002 crop, with samples containing up to 70% soybeans greenish (Lackey 2002). Lots with a high percentage of greenish soybean seeds or grains are classified as lower quality products, and their selling price is reduced. In the United States, classification grades for yellow soybeans are divided into 1, 2, 3, and 4, and the maximum established number of beans of other colors in samples for each classification grade is 1, 2, 5, and 10 percent respectively (USSEC 2006). Residual chlorophyll compromise the quality of seed material in terms of viability, nutritional value and shelf life, and pose a serious challenge for farmers (Smolikova et al. 2017). In rapeseed (*Brassica napus* L. var. Napus), carrot (*Daucus carota* L.), corn (*Zea mays* L.) and soybean (*Glycine max* L.), accelerated aging reduced germination to 61% in the seed sample with low chlorophyll content and to 30% in the sample of seeds with high chlorophyll content (Smolikova et al. 2011). The increased incidence of green seeds in soybean seed lots negatively affects their quality (Pádua et al. 2007). This reduction in quality occurs because the higher deterioration rate of green seeds results in abnormal seedlings, with non-uniform size and low root development, compared to seeds in which the chlorophyll degradation process has been completed (Forti et al. 2015). Drying soybeans at an air temperature of 25 °C allowed the degradation of chlorophyll in greenish grains harvested at stage R6 and later, causing green pigments to not be detected (Sinnecker et al. 2005). Drying soybeans at low temperatures may be a solution to eliminate the greenish grains in the post-harvest stage, however for the use of soybeans as seeds, this process is ineffective. Soybean seeds which are harvested immature and dried with ambient or heated air, with temperature variations between 25 °C to 29 °C, exhibited low germination, less than 32% (Samarah et al. 2009). Once that green soy is unfeasible for use as seeds, and that conventional processes carried out post-harvest are not enough to solve this problem, it's clear that the development of specific methods to separate the greenish grains from others is required.

The hypothesis of this work was that an accessible and robust optical device could address the separation of greenish from mature soybean seeds. Therefore, we aimed to test a feasible and a reliable setup with multiple artificial light sources, image capture and processing to provide the best achievement in separating greenish from mature soybean seeds.

The paper is structured in an Introduction of the theme addressing the problem of greenish soybean, and the importance of the classification. The Review of Literature pointed out the techniques developed so far to separate seeds using many methodologies. In the Material and Methods section, we detailed the methodology adopted to test the best configuration using artificial light sources and camera to acquire and process the images. The section also presented the image processing and statistical analysis of the data, finishing with a validation step. The Results and Discussion presented the best performances of the light sources adopted and the result of the validation test, finishing the paper with the Conclusion.

## Literature Review

The advancement of technology has provided useful improvements in our daily activities, of which agriculture is no exception, and has paved the way for new farming techniques all over the world (Abdulhamid et al. 2019). And the search for the implementation of innovative methods that automate traditional methods in agriculture is a constant effort, and one that precedes for a long time. Electric color sorters were used to sort beans in Michigan as early as the 1930s, the first machines used were slower than manual sorting, and their use was justified based on accuracy (Boyd Junior et al. 2021). And the increase in the processing capacity of microcomputers, made it possible to develop computer programs for seed evaluation. The Groundeye® software was able to progress the growth of coleoptiles and roots of popcorn hybrids, in a saline potential of -0.9 Mpa, and the evaluations through images performed with the software were efficient in the evaluation of the vigor of these seeds (Catão et al. 2020). The greenish soybean contains chlorophyll, which was not degraded in the maturation process, this characteristic can serve as a parameter for the segregation of these undesirable grains. Using the chlorophyll fluorescence technique, samples of soybean seeds of the cultivar TMG 113 RR were separated, sub-samples containing high and low chlorophyll fluorescence, and verified that the time for the seeds to reach 50% of maximum germination was shorter for seeds with low chlorophyll fluorescence, compared to ones that showed high chlorophyll fluorescence (Cicero et al. 2009). With the practicality and flexibility that computer resources provide, its application in agriculture contributes to the development of new techniques and equipment with the most diverse purposes. A seed sorter based on color was patented: the seeds were illuminated with strobe lights, which under a digital camera captured the images and sent them to a computer (Sheldon and Affleck 1990). Using computer vision in a prototype, it successfully identified impurity fractions in grains with an accuracy of 96% for split grains, 75% for contaminated grains, and 98% for defective grains, stems, and pods (Momin et al. 2017). The basis for the success of any machine vision application is high image quality, and normally, the contrast needed comes from the fashion the object is illuminated, and it is estimated that 90% of the applications can be solved just by selecting the lighting correctly (Blackman 2017).

## Materials and Methods

The soybean seeds used in the experiment were from the MG/BR 46-Conquista cultivar, produced in the 2014/2015 harvest at Fazenda Experimental Lageado, belonging to the Faculty of Agronomic Sciences - Unesp, located in the municipality of Botucatu, São Paulo, Brazil (22 °50'32" S; 48°25'29" W; 750 m altitude). Seeds were classified as mature and greenish according to the chlorophyll content determined by the High-Performance Liquid Chromatography method (Teixeira et al. 2016).

According to the Köppen classification, the climate of the region is characterized as humid hot temperate (mesothermal), CFA type, with an average annual rainfall of 1,501.4 mm and an average annual temperature of 20.3° C.

Images of mature and greenish soybean seeds were captured at a resolution of 340x480 pixels, illuminated with red laser, green laser, red LED, and fluorescent lamp. Subsequently, two groups of images were formed for each type of lighting, one group with 200 images of mature seeds, and the other with 200 images of greenish seeds.

#### *Image Acquisition and Lighting Adjustment*

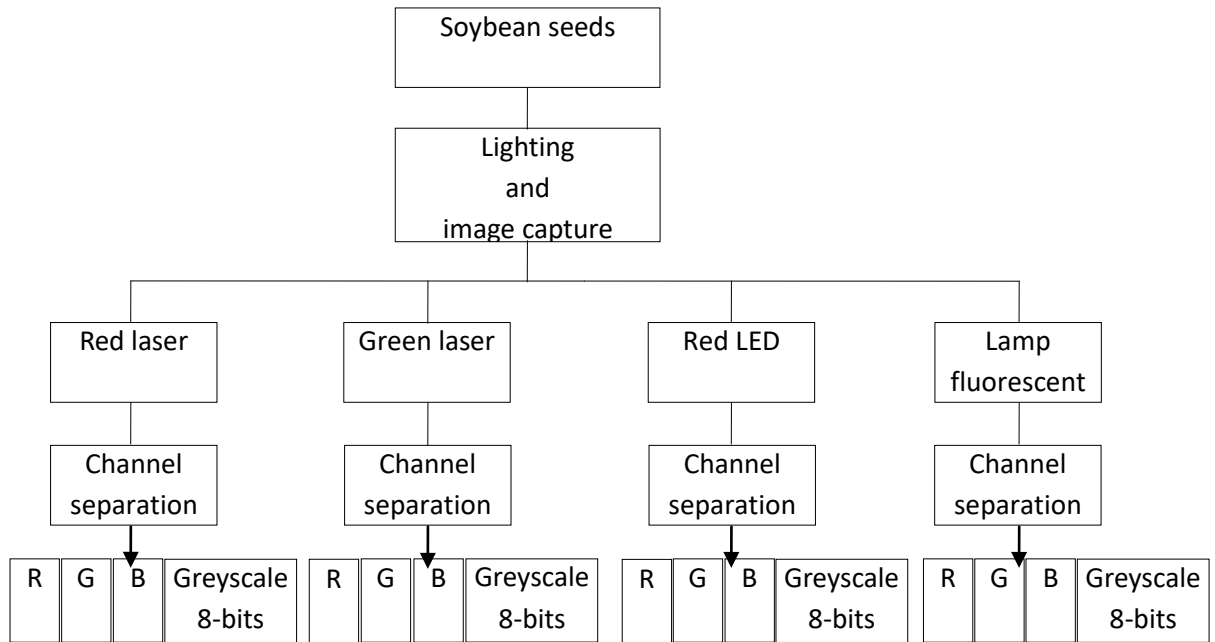
The intensity of the laser and LED lighting was controlled employing a neutral filter so that there was no saturation of the pixels by excess light. The luminosity of the fluorescent lamp was 245 lumens, measured with a digital lux meter. Images were captured using a Dino-Lite model AM211 digital camera, connected to a computer via a USB port. The seed was placed on a matte black background.

The control of the laser and LED light was done by monitoring the histogram of the image of a yellow-colored paper, which was used as a default background for the adjustment of the illumination intensity, with the averages of the gray levels shown by the histogram, stabilized at approximately 160 with the maximum value not reaching 255, indicating the absence of pixels saturated by excess lighting.

#### *Pre-Processing of Images*

Samples were taken from the region of interest for analysis and their images captured using the method previously described. Images of the seeds illuminated with fluorescent lamp were extracted in the resolution of 225x225 pixels, and images of the seeds illuminated with laser and LED were extracted in the resolution of 200x150 pixels.

Subsequently, the samples were duplicated into two groups, from one group the red, green, and blue (RGB) channels were separated, and the other group was converted to grayscale 8-bit. This procedure was done with the images of mature and greenish soybean seeds, in each type of lighting, organization chart 1 exemplifies the process of pre-processing the images. The total number of images used for analysis in each type of lighting was 1600, totaling, 6400 processed images.

**Organization Chart 1. Stages of Image Pre-Processing***Data Acquisition and Analysis*

The analyzed data is the average of the gray levels of the image samples, calculated by equation 1.

$$\mu_i = \frac{\sum_{k=1}^n (nck_i)}{n} \quad (1)$$

Where  $\mu_i$  is the average value of the gray levels of an image;  $nc$  is the pixel gray level value; and  $n$  is the total number of pixels in the image. The gray level averages were obtained using the ImageJ software. To verify the existence of statistical difference between the means, the data was submitted to the variance test at 5% probability.

*Classification of Images – Biasing and Validation*

The creation of a reference value of median for the gray scale images to separate the seeds was done in a group of 200 images of mature seeds and 200 images of greenish seeds. The median values of gray occurrences of 100 images, randomly selected from the two groups, were obtained and a umbral values – the mean of both medians – were set as references for classification. The classification of mature and greenish seeds was conducted, and the level of hits measured. Since all the seeds were tagged individually, with the primary classification in the two groups already known.

A procedure with one million interactions was carried out with the median and percentage of hits for mature classification identified. The means of medians values and hits were set as global reference to the validation step.

The classification references were set to the four types of illumination as well as to the channels of RGB and global gray.

The validation step used the 400 images – 200 from mature and 200 from greenish mixed – with the median values with the highest percentage of hits to mature seeds for all the treatments.

## Results and Discussion

### *References for Classification*

In the analysis of variance at 5% of probability, in all types of lighting, the differences between the average values of the gray levels of the images concerning the mature and greenish seeds, in the RGB channels and the images in grayscale 8-bits, were statistically significant with the P-value being 0.000 in all cases (Table 1). The next step was then to evaluate the best approach using the lighting and the channels of RGB or global gray.

**Table 1.** *Variance Analysis*

Variables	*CV (%)	General average	P value
<b>Fluorescent lamp</b>			
Red	4.32	174.89	0.000
Green	2.82	124.43	0.000
Blue	5.25	98.66	0.000
Grayscale 8-bits	4.16	132.65	0.000
<b>Green laser</b>			
Red	8.73	9.42	0.000
Green	6.72	87.51	0.000
Blue	9.35	38.49	0.000
Grayscale 8-bits	6.63	45.14	0.000
<b>Red laser</b>			
Red	7.77	136.62	0.000
Green	19.78	6.41	0.000
Blue	5.55	13.95	0.000
Grayscale 8-bits	6.03	52.33	0.000
<b>Red LED</b>			
Red	6	140.21	0.000
Green	25.21	4.56	0.000
Blue	10.60	8.12	0.000
Grayscale 8-bits	4.24	50.98	0.000

\*Coefficient of variation

In Table 2 it is shown the average gray levels of the images. The channel that conveyed the most considerable difference between the averages of gray levels was red, in the lighting with red laser, red LED and fluorescent lamp respectively. In lighting with green laser, the channel that revealed the most significant difference between the averages of gray levels was green; however, this difference



was smaller than the differences found in the red channel, of the other types of lighting evaluated. Evidencing that the images formed in the red channel, except when illuminated with green laser, were the ones that provided the best differentiation between the images of mature and greenish soybean seeds, and the efficiency in the differentiation is increased using the red laser.

**Table 2.** Overall Average of the Gray Levels of the Images

Seeds	8-bit gray scale	Red	Green	Blue
<b>Fluorescent lamp</b>				
<b>Mature</b>	137.07	183.23	127.1	100.88
<b>Greenish</b>	128.23	166.54	121.77	96.45
<b>Green Laser</b>				
<b>Mature</b>	47.25	9.13	91.68	40.94
<b>Greenish</b>	43.02	9.7	83.33	36.02
<b>Red Laser</b>				
<b>Mature</b>	56.92	151.51	4.77	14.49
<b>Greenish</b>	47.73	121.74	8.06	13.39
<b>Red LED</b>				
<b>Mature</b>	53.18	148.84	3.41	7.25
<b>Greenish</b>	48.77	131.57	5.72	9.00

#### *Classification of Images – Biasing and Validation*

Table 3 contains the data obtained in the validation of seeds classification. The red laser, red LED and fluorescent lamp, in the red RGB channel, achieved an efficiency rate above 90%.

When we consider the parameters False positive and False negative, which indicates the proportion of images of greenish seeds classified as mature, and images of mature seeds classified as greenish, respectively, we can conclude that the red laser illumination in the red RGB channel was the one that showed the highest efficiency, when compared to the other types of lighting and channels.

The errors can be attributed to the classification process proposed and also by the primary classification of the seeds in the field. In the field, the greenish seeds came from a parcel identified as greenish, but that can have some mature within. The high level of hits observed here leads us to conclude that the proposed method can be applied efficiently.

Gomes-Junior et al. (2016) evaluated a classification system by color of Swingle citrumele to identify at which stage of maturation the harvest should be carried out, to obtain seeds with greater physiological potential. And they found that the images in the red channel obtained greater differentiation between the gray levels of the images, of totally green, yellow-green, and yellow fruits. The results obtained with Swingle citrumele corroborate those of soybean seeds, since during their maturation stages, the color of the seeds also varies from green to yellow, as in the fruits of Swingle citrumele, consequently in both cases, the red channel of the images showed the greatest differentiation.

**Table 3.** Validation of Seed Classification – Test of Efficiency in Mature Seeds

	Hits (%)	False POSITIVE (%)	False NEGATIVE (%)
<b>Red laser</b>			
<b>Red channel</b>	97	6.5	3
<b>Green channel</b>	88	1.5	12
<b>Blue channel</b>	82	33	18
<b>Grayscale 8-bits</b>	96.5	7.5	3.5
<b>Green laser</b>			
<b>Red</b>	53.5	68	46.5
<b>Green</b>	85.5	28	14.5
<b>Blue</b>	82	37	18
<b>Grayscale 8-bits</b>	83.5	33	16.5
<b>Red LED</b>			
<b>Red</b>	93.5	16.5	6.5
<b>Green</b>	78.5	7	21.5
<b>Blue</b>	76.5	7.5	23.5
<b>Grayscale 8-bits</b>	93	17	7
<b>Fluorescent lamp</b>			
<b>Red</b>	94	14.5	6
<b>Green</b>	82.5	37.5	17.5
<b>Blue</b>	75	39.5	25
<b>Grayscale 8-bits</b>	87	27.5	13

## Conclusion

This work was able to successfully propose a methodology to classify soya bean seeds in mature and greenish. The optical method proposed identified the best option of lighting and channel of RGB to classify the seeds efficiently. The red channel of RGB images with red laser lighting presented an efficiency of 97% of hits. Other options as gray level outcome or the use of red and fluorescent light also presented high values of hits. The achievement offers to users robust and accessible alternatives to classify seeds non-destructively.

## Acknowledgments

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## Lowering Greenhouse Gases Emissions from the Energy and Oil Companies in the European Union: An Economic Overview

By Ștefania Mariana Voicu\*

*In the context of the Corporate Sustainability Reporting Directive (CSRD) that has been passed by the EU Parliament in November 2022 and which fundamentally changes the ways how companies reporting are made and the type of sustainability reporting made by the companies targeted by the directive, in this paper it is analyzed and examined, according with the forerunning directive, Non-Financial Reporting Directive (NFRD), which have been made compulsory by the European Union starting with year 2014, the improvements that have been effectively made in the emissions of greenhouse gases by the largest 6 companies in terms of revenue that operate primarily in energy, oil and gas industries (either by upstream, midstream or downstream sectors) and are of continental European origins. In this article are highlighted the economical efforts of combating the greenhouse gases (GHG) and the efficiency of the measures taken, both individually and collectively by the aforementioned conglomerates. It is also discussed the economic efficiency, both cumulative and separately for each of the analyzed companies. As well, an overview of the reduction importance of greenhouse gases is presented by exposing the environmental measurements since first being reported at a scientific level.*

**Keywords:** oil and energy industry, sustainable profitability, environmental responsibility, non-financial directives, green investments

### Introduction

Mobility is essential for society and the economy. At the same time, transportation is also a major cause of environmental pollution in the European Union (EU) and therefore also a part to climate change. Because of this, the importance of Corporate Sustainability Reporting Directive (CSRD) compulsory reporting is growing and alongside it the requirements for corporate sustainability reporting are as well changing radically. The new non-financial reportings that has to be generated according with the new EU directive on corporate sustainability reporting originated after the European Commission published its proposal for a directive in April 2021 and after the negotiators of the Commission, Council and European Parliament agreed on a compromise on June 21, 2022. The CSRD was formally adopted by the European Parliament and the Council and after being signed by the Presidents of the European Parliament and the Council on 16 December 2022 and published in the Official Journal of the European Union in 2022. The policy came finally into effect on January 5, 2023 and the new rulings have to be implemented by the member states after 18 months at the latest

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(Directive (EU) 2022/2464 2022).

However, certain public interest entities in the EU have been already required to report on their sustainability for a number of years. These have been regulated by the Non-Financial Reporting Directive (NFRD), which has been in force since 2014 (Directive (EU) 2014/95 2014). In this way, stakeholders should have been able to better assess the contribution of companies to sustainability. However, the current reporting obligations are now with the CSRD to be expanded considerably. As previously stated, in April 2021, the European Commission published its proposal for a Corporate Sustainability Reporting Directive (CSRD), which replaced the previously applicable Nonfinancial Reporting Directive (NFRD). The proposal has gone through the EU authorities and it was approved by the EU Parliament in November 2022 (Directive (EU) 2022/2464 2022). By this it is expected from the CSRD to expand the NFRD purposes and therefore to significantly enlarge the scope of the Sustainability Reporting.

In addition, all non-capital market-oriented companies are covered by the CSRD if they meet two of the following three criteria (Directive (EU) 2022/2464 2022):

- Total Revenue / Balance sheet > 20 million euros
- Net Sales > 40 million euros
- Number of employees > 250

The estimations are that around 50,000 companies in the EU would be affected (EU Press Release: 20221107IPR49611 2022).

We focus in this paper on the reporting of the biggest energy and petroleum companies that by the nature of their profile (S&P Global 2022, Statista.com 2022) are one of the biggest Greenhouse Gases (GHG) producers and at the same time contributors to the climate changing profile in European continental context, and their improvements and necessary costs for these.

## Literature Review

To better comprehend how the directives originated and their necessities, we put into perspective the Global and European context of Greenhouse Gases and how they affect every living organism on Earth.

As already proven, the Greenhouse gases (GHG) are gases that absorb and emit radiant energy within the thermal infrared range, causing the greenhouse effect (Seinfeld and Pandis 2016). The main greenhouse gases in the Earth's atmosphere are water vapor (H<sub>2</sub>O), carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O) and ozone (O<sub>3</sub>). Without the greenhouse gases, the Earth's average surface temperature would be around -18°C, (Seinfeld and Pandis 2016) instead of the current average of 15°C (Stocker et al. 2013, World Meteorological Organization (WMO 2019). The atmospheres of Venus, Mars, and Titan (moon of Jupiter) also contain greenhouse gases.

Human activities since the beginning of the Industrial Revolution (around the

year 1750) have increased the atmospheric concentration of Carbon Dioxide by almost 50%, from 280 ppm (parts per million) in 1750 to 419 ppm in 2021 (International Energy Agency 2020). The last time the atmospheric concentration of Carbon Dioxide as high as it now was over 3 million years ago (Blunden et al. 2017). This increase occurred despite the absorption of more than half of emissions by various natural carbon sinks in the carbon cycle (CAIT Climate Data Explorer 2023).

At current rates of greenhouse gas emissions, temperatures could rise by 2°C by 2050, which the United Nations Intergovernmental Panel on Climate Change (IPCC) says is the upper limit to avoid "hazardous" levels (Shishlov et al. 2016). The vast majority of anthropogenic carbon dioxide emissions come from the burning of fossil fuels, mainly coal, oil and natural gas, with additional contributions from cement manufacturing, fertilizer production, deforestation and other changes in land use (Grubb 2016, Rosen 2015, Kiehl and Trenberth 1997).

For a graphical description of all these information we can look at Figure 1 which it presents the evolution of the major Greenhouse Gases (GHG) emissions which have been released at a certain point in time in the planetary atmosphere. As it can be easily noticed, the percentage of the harmful gases to organisms lives have increased steadily since 1975 until the very recent years. The trend can be regarded as upwards for the most gases, in particular CO<sub>2</sub> with an absolute increase of 118% and therefore an angle percentage of 43.63% for the calibrated cumulative slope of the time period of 1975-2021 (CAIT Climate Data Explorer 2023).

The "saw-like" functions of the carbon dioxide (Figure 1A), nitrous oxide (Figure 1B), methane (Figure 1C) and even in chlorofluorocarbons (CFCs) and hydrochloro-fluorocarbons (HCFCs) (Figure 1D) can be correlated with the seasonal fluctuation. These fluctuations happen because of the seasonal variations. The main trends, also known as the Keeling curve, is plotted and visually demonstrated in Figure 2. It comprises the measurements of atmospheric CO<sub>2</sub> at Mauna Loa, Haway, which is the longest record that exists of such, respectively since 1958 until present modern days (Tans 2023, Keeling et al. 2001).

**Figure 1.** Evolution over Time of Atmospheric  $\text{CO}_2$  (1.A),  $\text{N}_2\text{O}$  (1.B),  $\text{CH}_4$  (1.C), CHC- and HFC-type (1.D) Gases

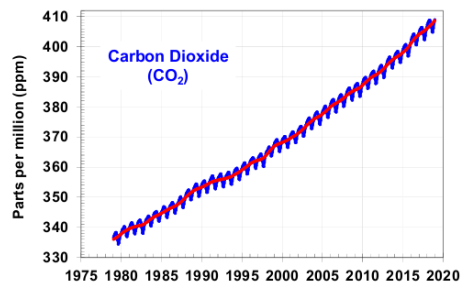


Fig. 1 A

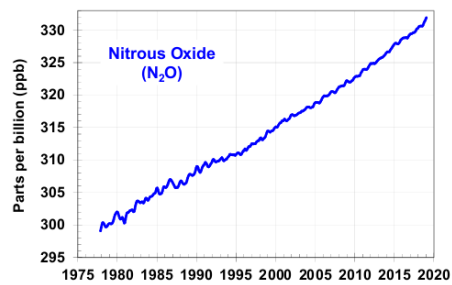


Fig. 1 B

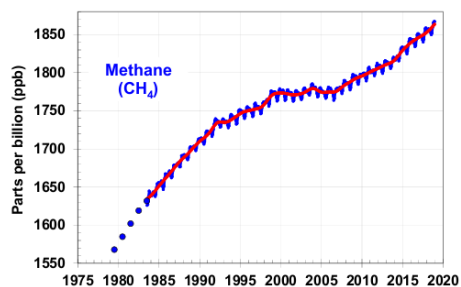


Fig. 1 C

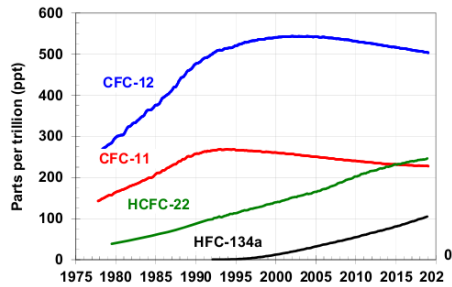
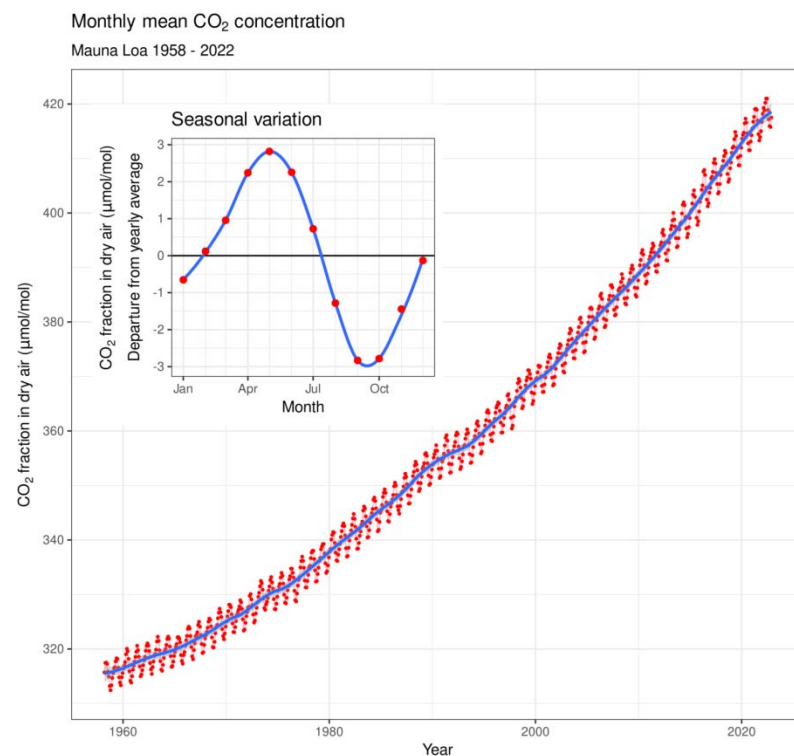


Fig. 1 D

Source: CAIT Climate Data Explorer via Climate Watch. [Accessed 15 May 2023]

**Figure 2.** Concentrations of Atmospheric  $\text{CO}_2$  Measured at Mauna Loa, Hawaii, 1958-2022



Source: <https://gml.noaa.gov/ccgg/trends/data.html>. [Accessed 15 May 2023]

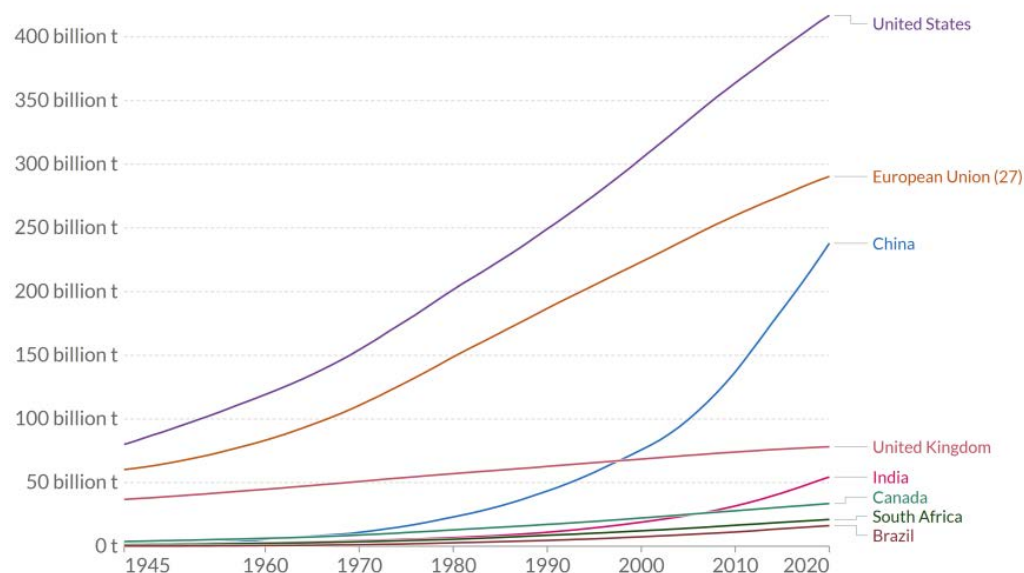


The annually curve that can be seen in the upper-left of the Figure 2 is caused by the removal of atmospheric CO<sub>2</sub> by the forests and land plants. As such, the density of forests which is more noticeable in the Northern Hemisphere, more carbon dioxide (CO<sub>2</sub>) is removed during the summer in Northern Hemisphere than in the Southern Hemisphere.

The curve that can be seen primary (central) in Figure 2 is known as the Keeling curve, after its discoverer, Dr. Ralph Keeling (Keeling et al. 2001). The trend, smothered by year's averages, can be seen as the blue curve, and the average monthly values are in this figure plotted with the color red. Independent researches in the world confirm the CO<sub>2</sub> measurements and altogether the Keeling curve (Norbedo et al. 2020, Gallo et al. 2019).

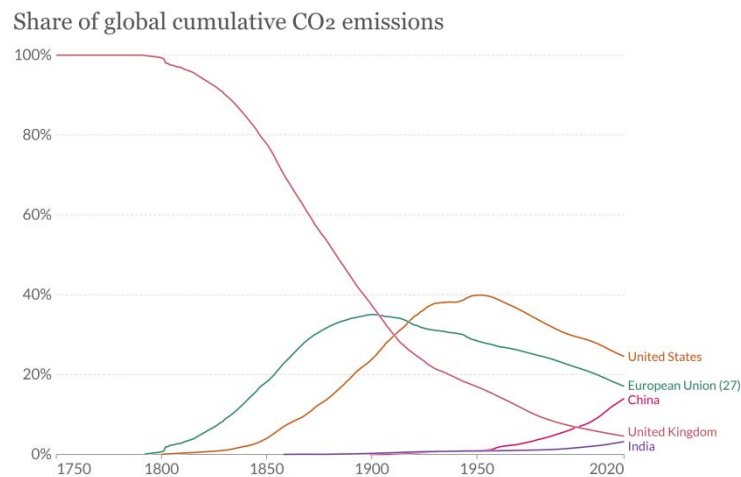
In terms of all time historical emissions to date we do mention United States, that have emitted up until now about 25% CO<sub>2</sub> emissions, which is about two times more than the next country responsible for this type of emission, China. The totality of countries from European Union (EU-28) are all time historically responsible for 22% of CO<sub>2</sub> emissions, as can be seen in Figures 3 and 4 (CAIT Climate Data Explorer 2023).

**Figure 3.** Cumulative CO<sub>2</sub> Emissions Grouped by Major Governing Entities  
Cumulative CO<sub>2</sub> emissions



Source: CAIT Climate Data Explorer via Climate Watch. [Accessed 15 May 2023]

**Figure 4.** *The Share of Global Cumulative CO<sub>2</sub> Emissions Grouped by Major Governing Entities*



Source: CAIT Climate Data Explorer via Climate Watch. [Accessed 15 May 2023]

## Methodology and Materials

The CSRD policy follows a double materiality perspective. This means that companies must record the impact of sustainability aspects on the company's economic situation. And they need to show the impact of operations on sustainability aspects. In reporting, the CSRD requires information on (Directive (EU) 2022/2464 2022):

- sustainability goals
- the role of the board of directors and the supervisory board
- the main adverse effects of the company, and
- to intangible resources not yet accounted for

In addition, with the new CSRD there is no longer the option of publishing non-financial information in a separate non-financial report. In the future, sustainability information should only be disclosed in the management report. The main innovations of the CSRD are presented as follows (Directive (EU) 2022/2464 2022):

- Extended, standardized reporting obligation:  
In the future, companies will have to report more comprehensively and according to more uniform standards. The measurability and comparability of the information should also be strengthened by quantifying the report content more effectively using indicators. The first drafts of the standards still to be issued by the EU Commission are currently being developed by EFRAG (European Financial Reporting Advisory Group) with the involvement of stakeholders and experts. Existing standards and regulations will be included.

- New understanding of materiality:  
The CSRD anchors the so-called double materiality. According to this, companies are obliged to report both on the effects of their own business operations on people and the environment and on the effects of sustainability aspects on the company. Previously, facts only had to be reported if both aspects of materiality applied.
- External audit:  
Sustainability reporting, like financial reporting, must be externally audited in the future. The EU Commission sets test standards for this. In addition, the depth of the audit is to be expanded step by step: In a first step, an audit with limited assurance is planned. And afterwards, according with the first audit, another audit with sufficient certainty ("reasonable assurance") is required, which corresponds to the depths of the audit in the context of financial reporting.
- Part of the management report:  
In order to facilitate access to sustainability information, it would be a mandatory part of the management report in the future. This shows the importance of sustainability reporting, which is gradually to be given the same importance as classic financial reporting.
- Uniform electronic reporting format:  
Since January 1, 2020, certain capital market-oriented companies have been obliged to disclose their accounting documents in the so-called European Single Electronic Format (ESEF), which is equally readable for humans and machines. Here, consolidated financial statements in XHTML format are marked with so-called XBRL tags. As part of the CSRD, this requirement is to be expanded to include sustainability reporting. To this end, the European Commission is planning to publish its own XBRL taxonomy.

Nevertheless, as mentioned before, other parts of CSRD reporting requirements have already been made compulsory by the EU Commission and with the help of NFRD we will analyze in the following the type of data that can be expected to be processed much faster because of the nature of changes made in the new European directive. We do mention, however, that our primary focus will be the Greenhouse Gases Emissions and the financial costs required to reduce these (Directive (EU) 2022/2464 2022, Directive (EU) 2014/95 2014).

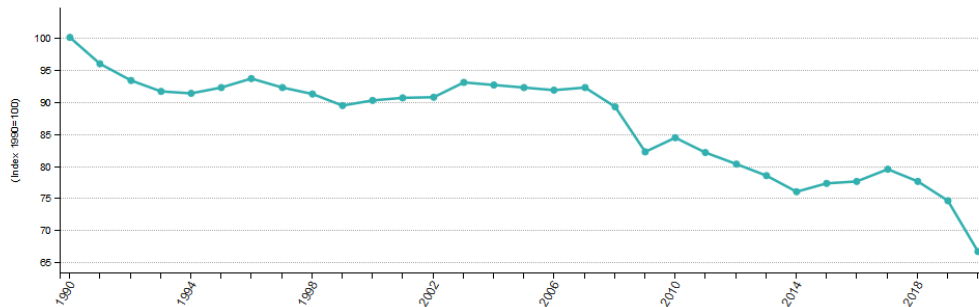
## Results

We can see improvements of reducing GHG emissions which are according with the plans of European Commission to reduce the GHG emissions by 55% in comparison with the levels of year 1990 until 2030 and start been carbon neutral by year 2050 (International Energy Agency 2021) The emission reduction were in year 2020 at a level of 66.7% compared to 1990, according with the statistical data from Eurostat, as it can be seen in Figure 5 and in Figure 6 as well (International

Energy Agency 2021, European Environment Agency 2023).

**Figure 5.** *Total Greenhouse Gas Emissions (Including International Aviation, excluding LULUCF) Trend, EU, 1990–2020 (Index 1990 = 100)*

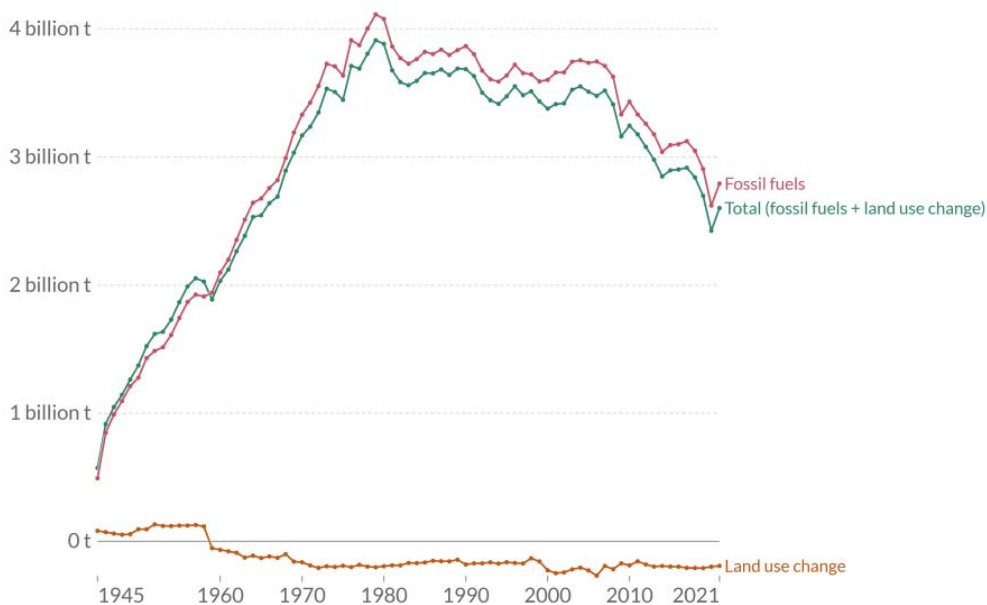
*Greenhouse gas emissions (including international aviation, excluding LULUCF) trend, EU, 1990 - 2020*



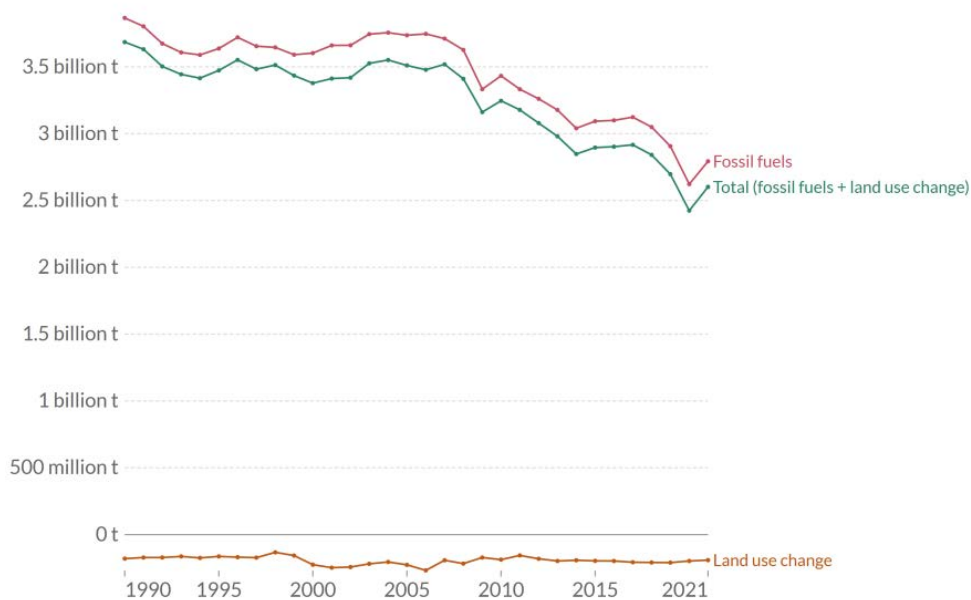
Source: European Environment Agency (online data code: env\_air\_gge). [Accessed 15 May 2023]

**Figure 6A.** *Which Plots the Global CO<sub>2</sub> Emissions from Fossil Fuels and Land Use Change for the Time Period 1945-2021 and Figure 6B. for the Time Period 1990-2021*

Global CO<sub>2</sub> emissions from fossil fuels and land use change, European Union (27)



### Global CO<sub>2</sub> emissions from fossil fuels and land use change, European Union (27)

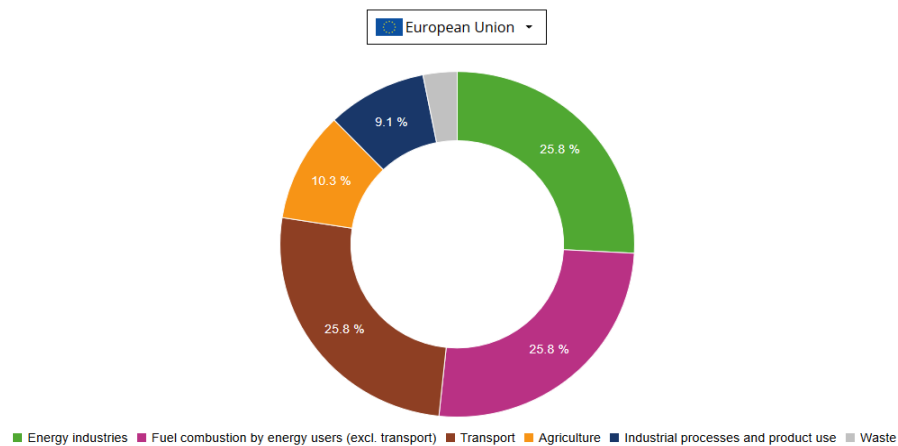


Source: CAIT Climate Data Explorer via Climate Watch. [Accessed 15 May 2023]

Out of all these emissions, around 25% are generated by energy and oil companies, as per official Eurostat data (European Environment Agency 2023).

**Figure 7. Emissions in 2019 by Industries (Pie-Chart)**

Greenhouse gas emissions by source, 2019  
(in %)



Data including international aviation, excluding indirect CO<sub>2</sub> emissions, excluding land use, land use change and forestry. Due to rounding data might not add up to 100 %.  
Source: European Environment Agency

Source: European Environment Agency (EEA), online data code: ENV\_AIR\_GGE. [Accessed 15 May 2023]

In the following we analyze the reduction of GHG emissions by the major 6 European Continental players in energy and oil industry in terms of revenue and employees, namely: Shell plc, BP p.l.c, TotalEnergies SE, Eni S.p.A, Repsol S.A and Equinor ASA.

## Discussion

In the latest five to seven years we noticed a substantial reduction of GHG emissions from the aforementioned companies and we strive to analyze the costs of such reductions according to the investments made by the respective corporations and at the same time to understand the necessary financial efforts made in order to reduce the emissions while maintaining the demanded energetic output and hold the attractiveness of the industry for the investors.

The most harmful GHG emissions are those of CO<sub>2</sub> and CH<sub>4</sub> because of the emitted quantity. However non-negligible are also those of the N<sub>2</sub>O and of course of the HFCs nature, which even though the companies are not required by the current legislation to make public knowledge the percentages of these 2 types of emissions (required to only disclose the CO<sub>2</sub>, CH<sub>4</sub> and the totality of GHG CO<sub>2</sub>e emissions), Shell plc (N<sub>2</sub>O and HFCs emissions) and Repsol S.A. (N<sub>2</sub>O emissions) decided to disclose the percentages to the public at large.

According with the lawful implementations in vigor and the reports issued by the corporations in question we try to analyze in the following the connections between the GHG emissions and some of the financial data, with a special focus on financial data from the investments made in lowering the Carbon Dioxide equivalent (CO<sub>2</sub>e) emissions, and also to comprehend to what degree / ratio have these harmful emissions been cut and how many financial efforts have been allocated especially for this purpose.

For the simplicity, in the followings, we will refer to the companies Shell plc as <<Shell>>, BP p.l.c as <<BP>>, TotalEnergies SE as <<Total>>, Eni S.p.A. as <<Eni>>, Repsol S.A. as <<Repsol>> and Equinor ASA as <<Equinor>>.

We present the Tables generated by the author, according with the Sustainability Reports and Financial Statements of the previous mentioned corporations, which contain the totality of GHG emissions, meaning the sum of Scope 1 (direct emissions from the Company's activities) and Scope 2 (indirect emissions associated with the purchase of electricity and steam from third parties) meaning, in other words, all the operated GHG emissions generated directly (Scope 1) and indirectly (Scope 2) by the corporations in question with the metric "million tonnes CO<sub>2</sub> equivalent", and the rest of the emissions data as been the direct emissions (Scope 1) as presented in the Sustainability Reports for operated emissions.

**Table 1.** *Shell GHG Emissions*

	Unit	2021	2020	2019	2018	2017
Total GHG Emissions (Scope 1 + Scope 2)	million tonnes CO <sub>2</sub> e	68 (60+8)	71 (63+8)	80 (70+10)	82 (71+11)	85 (73+12)
Carbon dioxide (CO <sub>2</sub> )	million tonnes	58	61	67	69	70
Methane (CH <sub>4</sub> )	thousand tonnes	55	67	91	92	123
Nitrous oxide (N <sub>2</sub> O)	thousand tonnes	1	1	1	1	1
Hydrofluorocarbons	tonnes	25	30	29	31	22

	Unit	2021	2020	2019	2018	2017
(HFCs)						
Investments in Low-Carbon Energy	Millions (\$)	2359	928	1134	748	172

Source: Shell plc Sustainability Report 2021, 2020, 2019, 2018.

**Table 2. BP GHG Emissions**

	Unit	2021	2020	2019	2018	2017
Total GHG Emissions (Scope 1 + Scope 2)	million tonnes CO <sub>2</sub> e	35.6 (33.2+2.4)	45.5 (41.7+3.8)	54.4 (49.2+5.2)	54.2 (48.8+5.4)	56.6 (50.5+6.1)
Carbon dioxide (CO <sub>2</sub> )	million tonnes	30.3	38.8	43.0	43.3	45.8
Methane (CH <sub>4</sub> )	Thousand tonnes	50	70	100	90	110
Environmental Expenditures	Million (\$)	2195	412	2319	1546	971

Source: BP ESG annual reports 2021, 2020, 2019, 2018.

We also analyzed the investments made by BP in order to make the transition towards a greener future of the company which according to BP official datasheet <<majority of which related to investments in offshore wind, electric vehicle charging infrastructure and solar>> while at the same time trying to preserve the competitiveness of the market in order to be seen as healthy by investors (BP 2021).

**Table 3. Total Energies GHG Emissions**

	Unit	2021	2020	2019	2018	2017
Total GHG Emissions (Scope 1 + Scope 2)	million tonnes CO <sub>2</sub> e	37 (34+3)	41 (38+3)	44 (41+3)	44 (40+4)	42 (38+4)
Carbon dioxide (CO <sub>2</sub> )	million tonnes	32	34	39	39	38
Methane (CH <sub>4</sub> )	thousand tonnes	1	2	2	2	2
R&D Expenditure (total)	millions (€)	849	895	968	986	912
R&D Expenditure related to decarbonization	millions (€)	114	74	102	74	72

Source: Total Sustainability reports 2021, 2020, 2019.

**Table 4. Eni GHG Emissions**

	Unit	2021	2020	2019	2018	2017
Total GHG Emissions (Scope 1 + Scope 2)	million tonnes CO <sub>2</sub> e	40.89 (40.08+0.81)	38.49 (37.76+0.73)	41.89 (41.2+0.69)	44.02 (43.35+0.67)	43.8 (43.15+0.65)
Carbon dioxide (CO <sub>2</sub> )	million tonnes	30.58	29.70	32.27	33.89	33.03
Methane (CH <sub>4</sub> )	thousand tonnes	9.2	11.9	21.9	38.8	38.8
R&D Expenditure (total)	millions (€)	177	157	194	197.2	185
R&D Expenditure related to decarbonization	millions (€)	114	74	102	74	72

Source: Eni annual reports 2021, 2018.

**Table 5. Repsol GHG Emissions**

	Unit	2021	2020	2019	2018	2017
Total GHG Emissions (Scope 1 + Scope 2)	million tonnes CO <sub>2</sub> e	19.8 (19.4+0.4)	22.9 (22.4+0.5)	25.2 (24.7+0.5)	22.4 (22.0+0.4)	23.4 (23.0+0.4)
Carbon dioxide (CO <sub>2</sub> )	million tonnes	17.1	19.0	20.1	17.9	18.4
Methane (CH <sub>4</sub> )	thousand tonnes	27.4	39.3	53.6	48.8	51.1
Nitrous oxide (N <sub>2</sub> O)	thousand tonnes	0.34	0.35	0.27	0.13	0.07
Expenditures (CO <sub>2</sub> allowances)	million (€)	479	281	325	113	69
Net cost of carbon management	million (€)	220	96	132	44	17

Source: Repsol annual report 2021, 2019.

For the Methane and N<sub>2</sub>O it was the method of converting CO<sub>2</sub> equivalent to CH<sub>4</sub> absolute values by dividing the values (million tones CO<sub>2</sub>e) of CH<sub>4</sub> and N<sub>2</sub>O reported by the company by 84 and 298 respectively, and transformed into thousand tonnes, which is been considered in this article for the sake of the continuity as the industry standard (IPCC 2023, US Environmental Protection Agency 2023).

**Table 6. Equinor GHG Emissions**

	Unit	2021	2020	2019	2018	2017
Total GHG Emissions (Scope 1 + Scope 2)	million tonnes CO <sub>2</sub> e	12.1 (12.0+0.1)	13.6 (13.3+0.3)	14.9 (14.7+0.2)	15.1 (14.9+0.2)	15.6 (15.4+0.2)
Carbon dioxide (CO <sub>2</sub> )	million tonnes	11.7	12.9	14.2	14.5	14.9
Methane (CH <sub>4</sub> )	thousand	14.5	17.7	18.1	19.1	19.3



	Unit	2021	2020	2019	2018	2017
	tonnes					
R&D expenditure on low-carbon projects	millions (\$)	95	81	59	66	55
R&D expenditure to new energy solutions and efficiency	% (of total R&D expenditures)	33	32	20	21	18

Source: Equinor Sustainability report 2021.

In the following figures we can easily see the progress made by each company in terms of emission of hurtful gasses in the Planetary Atmosphere. Figure 8 shows the reduction of the CO<sub>2</sub> emissions by each company that we analyzed, while Figure 9 depicts the CH<sub>4</sub> reduction, as well for all companies analyzed.

**Figure 8.** Represents the CO<sub>2</sub> Emissions Each Year (for the Period 2021-2017) for Each Company with the Representations A – CO<sub>2</sub> Emissions from the Company Shell, B from the Company BP, C from Total, D from Eni, E – Repsol and F – Equinor Respectively

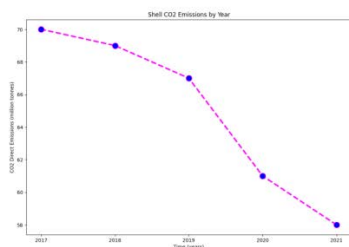


Fig. 8 A

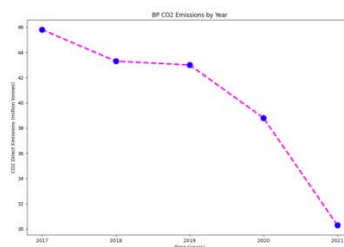


Fig. 8 B

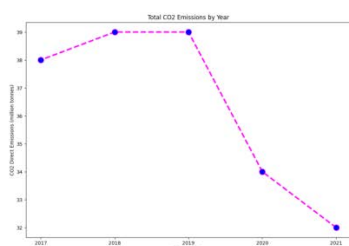


Fig. 8 C

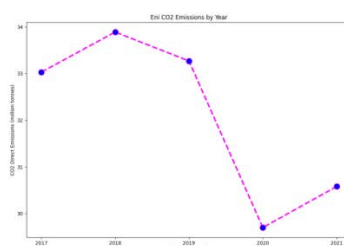


Fig. 8 D

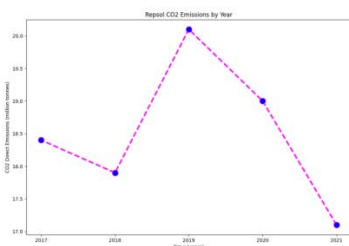


Fig. 8 E

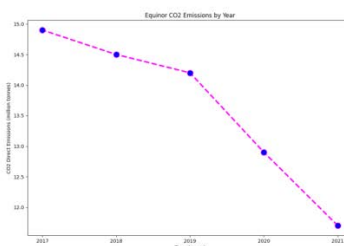


Fig. 8 F

Source: Own computation based on analyzed companies' sustainability reports.

**Figure 9.** *CH<sub>4</sub> Emissions Each Year (for the Period 2017-2021) for Each Company with the Representations A – CO<sub>2</sub> Emissions from the Company Shell, B from the Company BP, C from Total, D from Eni, E – Repsol and F – Equinor Respectively*

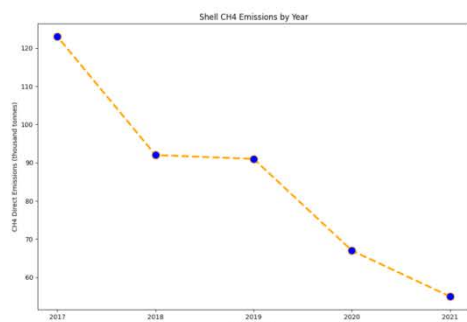


Fig. 9 A

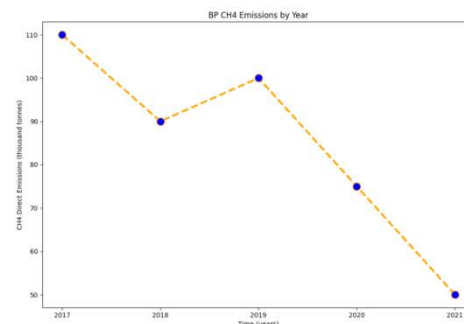


Fig. 9 B

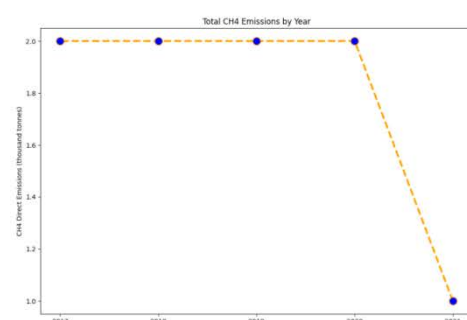


Fig. 9 C

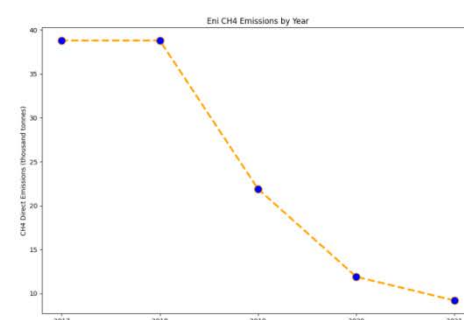


Fig. 9 D

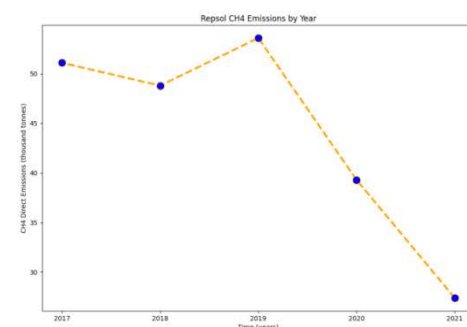


Fig. 9 E

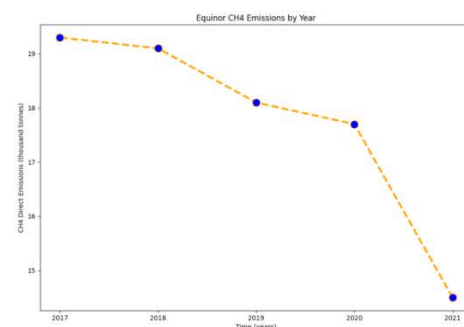


Fig. 9 F

Source: Own computation based on analyzed companies' sustainability reports.

In terms of total GHG emissions reductions (calculated in CO<sub>2</sub>e) we see in the following the progress made by each company separately and as well side-by-side comparisons with the efficiency percentages year-on-year. With the scope of further analysis, the performances of the rest of companies not presented in this section, can be found in Annex A.

**Figure 10A. & B.** Side-by-Side Comparison between the Companies (Shell) that Succeeded to Mostly Reduce its GHG Emissions in Figure 10A and the Least Efficient Company (Total) in Terms of Totally GHG Reductions in Figure 10B

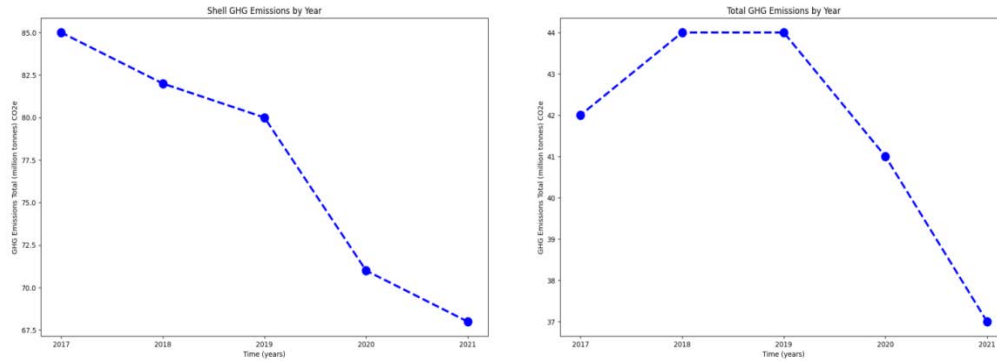


Fig. 10 A

Fig. 10 B

Source: Own computation based on analyzed companies' sustainability reports.

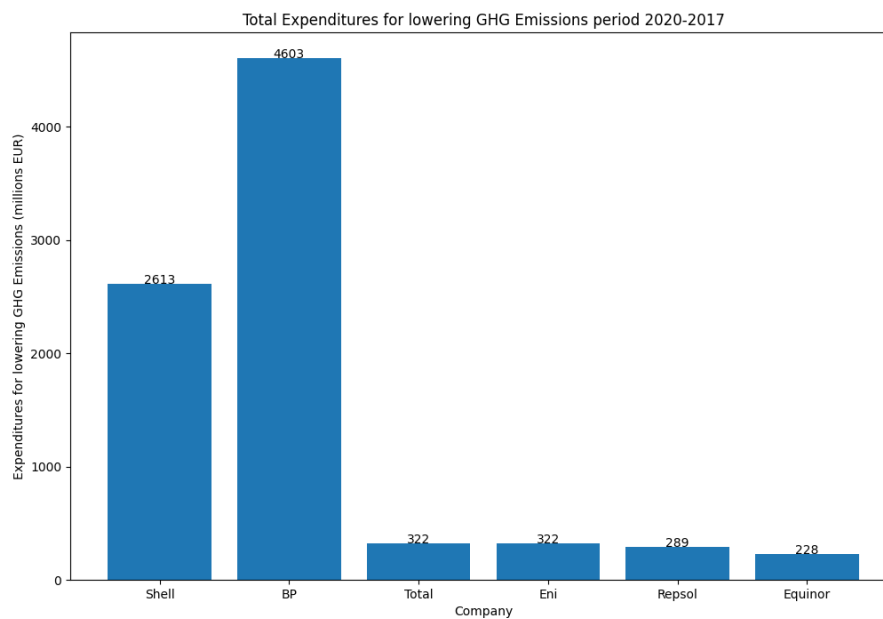
## Analysis

We also present in the following figure the total costs of the 6 companies over all the years presented in this article and the following the efficiency in millions EUR per 1 million tonne CO<sub>2</sub>e over all the same period of time. In order to do this and thoroughly analyze the financial costs and their efficiency we convey the following formulas that will be used essentially to calculate the efficiency of the investments in lowering the CO<sub>2</sub>e fingerprint for each of the six companies:

$$TotalInvestments(company) = \sum_{year=2017}^{2020} investment_{year}(company) \quad (A)$$

Please note the beginning and end-years that were chosen for this particular formula. The investments sums start from the first year analyzed and stop at the penultimate year from this study, the reasoning being that the investments made in year  $x$  are first to be seen (in terms of GHG-emissions reductions) during year  $x + 1$  (e.g., investments made in year 2018 are first to be seen during year 2019, those made in year 2019 will be first seen during the emissions for 2020 and so on).

**Figure 11.** Total Sums Invested over the Period of Time 2020-2017 for all the Companies Analyzed



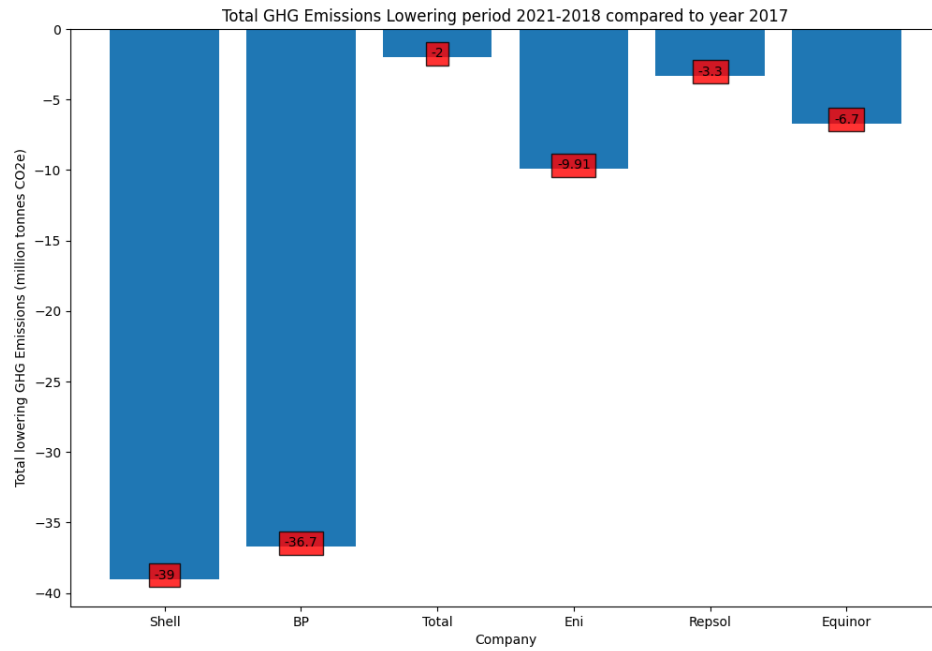
Source: Own computation based on analyzed companies' sustainability reports.

The method for which the differences in terms of total GHG emissions reductions are calculated with regard to the first year analyzed (2017) if the emissions would have stayed at the same level of year 2017, is the following:

$$TotalGHGEmissionsreductions(company) = \sum_{year=2018}^{2021} [GHGEmissions_{year}(company) - GHGEmissions_{2017}(company)]^{(B)}$$

Again, please note the begin and end-years of the formula, which are in according with the previous equation, (A).

**Figure 12.** Totality of GHG Emissions Reductions Calculated in Million Tonnes CO<sub>2</sub>e over the Time Period 2021-2018 Compared to Year 2017

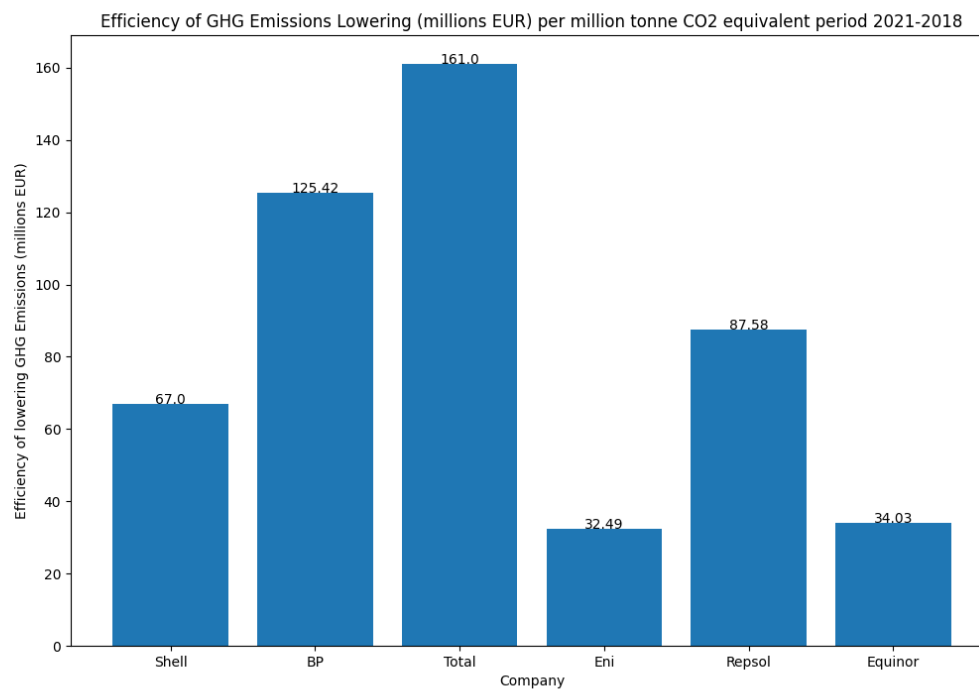


Source: Own research.

In order to determine the efficiency of the many invested during period of time 2020-2017 we do use the following equation:

$$\begin{aligned}
 InvestmentsEfficiency(company) &= \frac{TotalInvestments(company)}{TotalGHGmissionsreductions(company)} \\
 &= \frac{\sum_{year=2017}^{2020} investment_{year}(company)}{\sum_{year=2018}^{2021} [GHGmissions_{year}(comapny) - GHGmissions_{2017}(company)]}
 \end{aligned}$$

**Figure 13.** *Totality of GHG Emissions in CO<sub>2</sub>e Million Tonnes over the Period 2021-2018 Compared to Year 2017*



Source: Own research.

One can easily see from Figure 13. that the most efficient company in terms of expenditure per reduced million tonne CO<sub>2</sub>e was Eni and the least efficient one in terms of investments was Total with 161 millions EUR per million tonne, meaning a difference of almost ~500% between the two companies.

## Conclusions

The introduction of the non-financial statements by the European Union through Reporting Directives was and still is of great environmental and economic value for all the parties involved, not only for research purposes, but also for informative ones, that could be used by investors or by the general public in order to see and recognize the evolution of the environmental progresses according with the United Nations' Sustainable Development Goals (SDGs) or with the European goals.

According to the official financial and non-financial statements issued yearly in the past 5 years (2017-2021) by the 6 companies in relationship to the NFRD, an estimated cumulative effort of these companies by more than 5 billions EUR has been made only in year 2021, in order for the GHG emissions to be reduced by a weighted ~ 9% compared to the prior year (2020) and by almost ~ 19% compared to reference year 2017.

We can also see, after closer examination, that total year by year CO<sub>2</sub>e emission reduction progress averaged from ~ 10.06 % (year 2020 compared to 2019) to a negative progress of ~ -0.71 % (from year 2019 to year 2018) for the 5 year period analyzed. As well, across the companies analyzed in this paper, the most expensive spending done during this period was made by the company BP p.l.c. with ~ 4.6 bn EUR and the least sum was spent by Equinor ASA with the total sum of 228 millions EUR. With the total absolute cost spent during the period 2021-2017 of ~ 8377 millions EUR it was possible an average reduction year-on-year by ~ 5 % of total GHGs emissions starting from the reference year 2017 and until 2021, with an average of ~ 101.5 millions EUR per million tonnes CO<sub>2</sub>e reduction. The total sum in oil, gas and energy industry spent during the years 2017 – 2021 for reducing the output of CO<sub>2</sub>e by all the 6 companies analyzed was 12756 millions EUR, which prevented, during the same period of time, more than 1234 million tonnes CO<sub>2</sub>e to be emitted.

The Non-Financial Reporting Directive (NFRD) implementation in 2014 was an initiative that shed light on many industries that contributes to the pollution of the Planetary Atmosphere, and one of the industries that could be categorized as a big polluter is the oil, gas and energy industry. In the light of the new special directive, Corporate Sustainability Reporting Directive (CSRD), that extends the previous directive, NFRD, we examined and compared the reported non-financial data provided by the largest 6 European based energy companies and correlated it with the financial investments and analyzed the efficiency of each company in reducing the greenhouse gasses (GHG) emissions and its effects.

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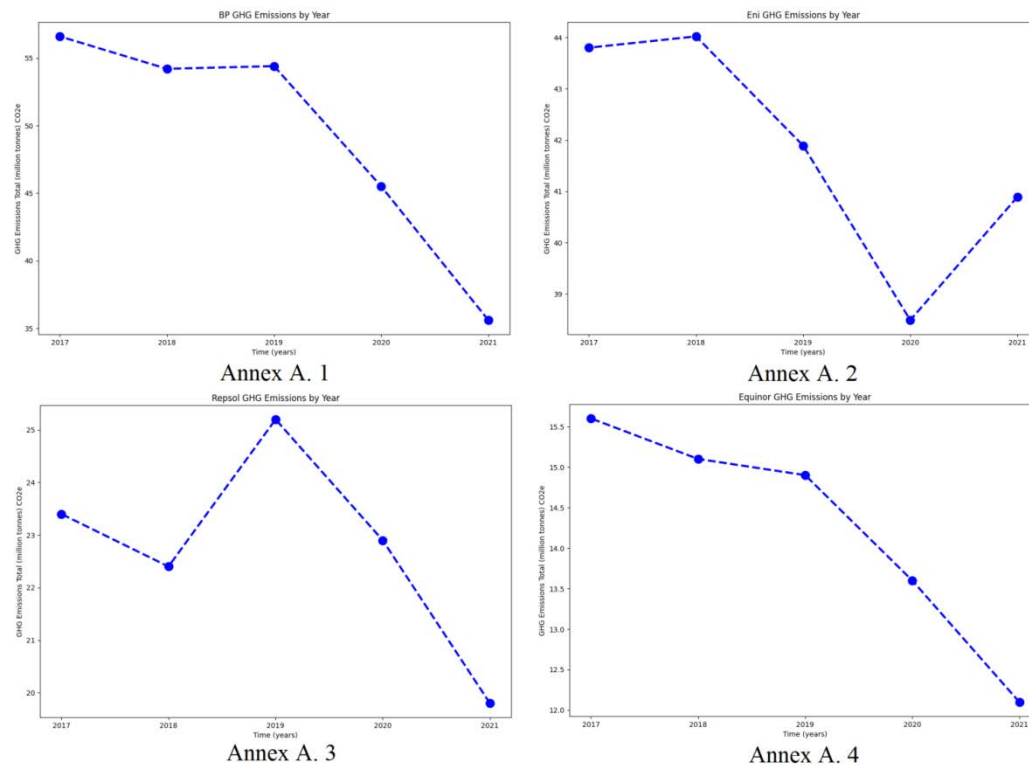
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## Appendix

*Total GHG Emissions Reductions (Calculated in CO<sub>2</sub>e) from BP (Annex A.1), Eni (Annex A.2), Repsol (Annex A.3) and Equinor (Annex A.4) for the Period 2017–2021*



Source: Own illustration based on analyzed companies' sustainability reports.

### *Historical Reference Rates 2017-2021 USD to EUR*

Year	2021	2020	2019	2018	2017
USD/EUR Rate	0.8458	0.877	0.8931	0.8475	0.8865

Source: European Central Bank. [Accessed 15 May 2023]



## The International Space Station (ISS) Contest as STEM Educational Project

By Enzo Bonacci\*

*In the years 2015–2018, the Italian Ministry of Education, University and Research and the Italian Ministry of Defense proposed the joint initiative "Space for Your Future. The ISS: Innovatio, Scientia, Sapientia" in partnership with the Italian Space Agency. It was a competition addressed to secondary school students and aimed at developing innovative experiments to be conducted on the International Space Station, whose acronym (ISS) is the same of the Latin words "Innovatio, Scientia, Sapientia". Regardless of the odds of winning, "Space for Your Future" became a successful STEM educational project implemented in numerous schools. We illustrate how that Astronomy contest fostered a valid constructivist learning, a fruitful participatory science, and vast scientific research. We discuss, in particular, the activities of two teams of pupils from the Scientific High School "Giovanni Battista Grassi" in Latina (seat of the Planetarium "Livio Gratton") who participated within the thematic area No. 3 "Test the Sciences in Space". They all worked on chemical tests, suitable for the ISS microgravity, under the tutoring of Francesco Giuliano (Province Manager of the IYA 2009 and the IYC 2011 in Latina). The key reference is a talk given in the 104th annual congress of the Italian Physical Society at the University of Calabria (September 17–21, 2018) together with an invited lecture held in the 13th European Researchers' Night by Frascati Scienza (September 28, 2018).*

**Keywords:** science contest, ISS, secondary school, educational project, TRL, STEM, constructivism, PBL, PrBL, learning by Doing, IBSE, citizen science, ESD, EDP.

### Introduction

Launched jointly by the Italian Ministry of Education, University and Research (MIUR for brevity) and by the Italian Ministry of Defense (MDI for short), the contest "Space for Your Future. The ISS: Innovatio, Scientia, Sapientia" had a slow start in 2015 (Figure 1), despite the collaboration with the Italian Space Agency (ASI). Only after a persuasion campaign led by the Italian cosmonaut Lieutenant Colonel Walter Villadei, the MIUR-MDI-ASI's initiative was understood in its ambitious purpose of connecting the School to Space research and welcomed as a big opportunity to improve the teenagers' attitude towards STEM (Science, Technology, Engineering and Mathematics). The Italian cosmonaut elucidated how the Latin words "Innovatio, Scientia, Sapientia", translatable as "Innovation, Science, Wisdom", had been accurately chosen for both their meaning and acronym (ISS) identical to the famous International Space Station. He explained that each secondary school could compete with maximum

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\*Teacher, formerly at Scientific High School "G.B. Grassi" of Latina, Italy.

three teams, picked from the 4th and 5th year's pupils (ages 17–19) and preferably steered by mentors from accredited institutions.

**Figure 1.** *The 2015 Official Poster of the ISS Competition for Italian Schools*



Source: <https://bit.ly/3qMJYzJ>.

Walter Villadei clarified that some of the selected works would possibly be tested in microgravity conditions right on board the ISS (orbiting 400 kilometres above the Earth). In his tour across Italy (Fig. 2), he expounded that "Space for Your Future" was conveniently divided into the following seven thematic areas:

1. "From daily life to Space": proposals to improve the lives of astronauts aboard the International Space Station.
2. "Train like an astronaut": proposals for the development of physical exercises, sensors, and tools to improve the efficiency of physical exercise on board, also through new protocols and new strategies usable for the training of astronauts in a simulated situation on earth.
3. "Test the Sciences in Space": proposals for activities and/or experimental protocols of natural sciences, physics, chemistry, and biology aimed at learning about the space environment and also aimed at highlighting the differences between the space and terrestrial environment.
4. "Observe the Earth to guard it": proposals for the development of computer applications (App) related to Earth observation, the development of thematic catalogs, new observational techniques, or the use of innovative tools to monitor our habitat, protect it and preserve it.

5. "Stay connected with an astronaut": proposals for the development of computer applications (App) aimed at interacting directly with astronauts and bringing the life of the astronaut on board the Space Station closer to the daily life of students on the ground.
6. "Robots, satellites and astronauts conquering the Universe": proposals for the development of microsatellite prototypes, automatic systems interacting with humans, prototypes and/or advanced robotics experiments on board the ISS.
7. "Cultivate in space to cultivate better on Earth": project proposals for the development of new cultivation techniques in the space environment that can also provide information on how to use available resources in hostile environments.

**Figure 2.** *Walter Villadei Presents the ISS Contest in Latina (May 27, 2016)*



Source: <https://bit.ly/3CfzL2b>.

Fifty-four Italian schools joined the ISS competition through STEM educational projects based on constructivist methods, principally Problem and Project Based Learning (PBL & PrBL), which enhanced the Inquiry Based Science Education (IBSE), the Education for Sustainable Development (ESD), the Engineering Design Process (EDP), and the Information & Communication Technologies (ICT). Here we offer an overview of the competition, from the first call for applications (December 15, 2015) to the awarding ceremony (March 14, 2018), with a brief mention to the forerunner SUCCESS student contest by ESA<sup>1</sup>. Later we focus on the contribution from the Scientific High School "G.B. Grassi" of Latina (Lazio region), whose pupils formulated two chemical experiments in mini

<sup>1</sup><https://bit.ly/3LXGQcz>.

containers. Most of the material about that inspiring STEM activity comes from a topical talk (Bonacci, 2018a) and a public lecture (Bonacci, 2018b) meant to be rigorous (Heigl et al., 2019), accessible and engaging, as auspicated by the European Citizen Science Association<sup>2</sup>. The legal framework and an up-to-date literature are retrieved from current institutional and sectorial websites.

### **The Trailblazing Student Contest SUCCESS by ESA**

As outlined in the Fifty-fourth session of the United Nations Committee on Peaceful Uses of Outer Space (COPUOS): "Since 1998, when the first modules were launched, the ISS has been assembled by a partnership of five space agencies (CSA, ESA, JAXA, NASA, and Roscosmos) representing 15 countries. The unique features of the ISS are: robust, continuous, and sustainable microgravity platform; continuous human presence in space; access to the ultra-high vacuum of space; unique altitude for observation and testing; and payload-to-orbit-and-return capability."<sup>3</sup> As soon as the International Space Station was ready, the European Space Agency (ESA) ran the *Space station Utilisation Contest Calls for European Student initiativeS* (SUCCESS): "a competition for European university students from all disciplines to propose an experiment that could fly on board the ISS."<sup>4</sup> The SUCCESS contest acquired a fair notoriety in 2005, when a selected experiment was really conducted on board the International Space Station (Fig. 3). ESA's SUCCESS paved the way for similar competitions such as the Italian *Space for Your Future* (targeted on secondary schools) we examine in the next paragraph.

### **Space for Your Future - The ISS: Innovatio, Scientia, Sapientia**

*The ISS First Call for Applications in 2015 (Deadline March 31, 2016)*

On December 15, 2015, the Italian Ministry of Education, University and Research launched "the competition *Space for Your Future. The ISS: Innovatio, Scientia, Sapientia* addressed to pupils of fourth and fifth years of high schools, technical and professional institutes. Through the competition, aimed at the dissemination and promotion of scientific activities and technologies in the space sector, students will be involved in the conception of innovative experimentation proposals to be taken aboard the International Space Station. Students will be asked to develop experimentation proposals (actual artifacts and/or experimentation protocols), to be carried out on board the International Space Station, based on the technical and scientific skills acquired during the schooling period and subsequently elaborated with the support of the teachers. and the sponsoring organizations of the initiative" (translated from the MIUR Note No. 13482, Italian website<sup>5</sup>).

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<sup>2</sup><https://bit.ly/3juKZJ5>.

<sup>3</sup><https://bit.ly/3oQRtVN>.

<sup>4</sup><https://bit.ly/3zdcAD3>.

<sup>5</sup><https://bit.ly/3AyfEv1>.

**Figure 3.** Hardware of Bone Proteomics Flown on the ISS in April 2005

Source: <https://bit.ly/40I9ZNb>.

#### *The ISS Second Call for Applications in 2016 (Deadline March 31, 2017)*

On September 16, 2016, the MIUR revised the flyer (Figure 4) and some aspects of the regulation, included the contest's deadline (extended until March 31, 2017) and the description of the definitive project:

"Scope the final project represents the conclusive work (final report) prepared by the teams joining the "School: space for your future" initiative and which will be presented for subsequent evaluation by the Commission set up for the Competition Announcement. The Final Projects must contain proposals for experiments to be carried out in space and/or on board an orbiting platform (primarily ISS) within the thematic areas described in the Competition Rules.

Requirements the *Final Project* must meet some requirements:

- expose contents consistent with the premises proposed in the preliminary project, in terms of thematic areas and proposed objectives;
- report plainly the working methods adopted;
- describe the various logical, experimental and investigation phases of the works;



- report in detail the national or international bibliographic sources referred in the works;
- report a minimum structure including: "Index of topics", "Materials and Methods", "Activities carried out", "Conclusions".

Specific chapters functional to evidence the activities carried out, with a logical-consequential structure, may then be added.

**Figure 4.** The 2016 Official Poster of the ISS Competition for Italian Schools



Source: <https://bit.ly/468Cl6E>.

Working methods different kind of *Definitive Projects* can be elaborated: compilation, theoretical, numerical-analytical, experimental. In the case of numerical-experimental projects it will be necessary to report any algorithms and the conceptual structure of the paper. In the case of experimental projects, an accurate and documented description of what has been done will be required. The use of aids such as graphics, images, diagrams, videos will be allowed in order to



give evidence of the envisaged results. Any demonstrators or artefacts (technological or scientific) exemplifying the activity carried out and/or the results achieved will be admitted, provided they are complete with adequate explanations. Simulation tools based on commercial software or developed by students using the coding languages they know are also admitted." (translated from the MIUR Note No. 10475, Attachment No.3, Italian website<sup>6</sup>).

*The ISS Third Call for Applications in 2017 (Deadline May 31, 2017)*

On February 23, 2017, the Italian Ministry of Education, University and Research recorded 110 *preliminary* projects<sup>7</sup> presented by 54 schools from 12 regions (Fig. 5) and 33 provinces (Fig. 6). Hence, on March 30, the MIUR announced that "following the numerous requests received from schools and in order to allow more time in the development and processing of experimentation projects, also considering their complexity, the deadline for the submission of the related projects, already set for March 31, 2017, is extended to May 31, 2017" (translated from the MIUR Note No. 3480, Italian website<sup>8</sup>).

Let us notice how the *ISS* challenge was faced positively at all latitudes of the Italian peninsula and in Sicily (Fig. 6).

Since the Italian secondary schools respond to local administrations (regional or provincial, depending on their curricula), we have arranged the geographic distribution of the presented projects in Table 1. The Province of Latina (agro-industrial hub in southern Lazio) joined the *ISS* competition with two secondary schools: the Institute of Higher Education "San Benedetto" and the Scientific High School "G.B. Grassi". The latter<sup>9</sup> hosts the Planetarium "Livio Gratton", a mighty driver of STEM projects (Bonacci, 2011b, 2016a, 2016b) and participatory science (Bonacci, 2017c, 2020).

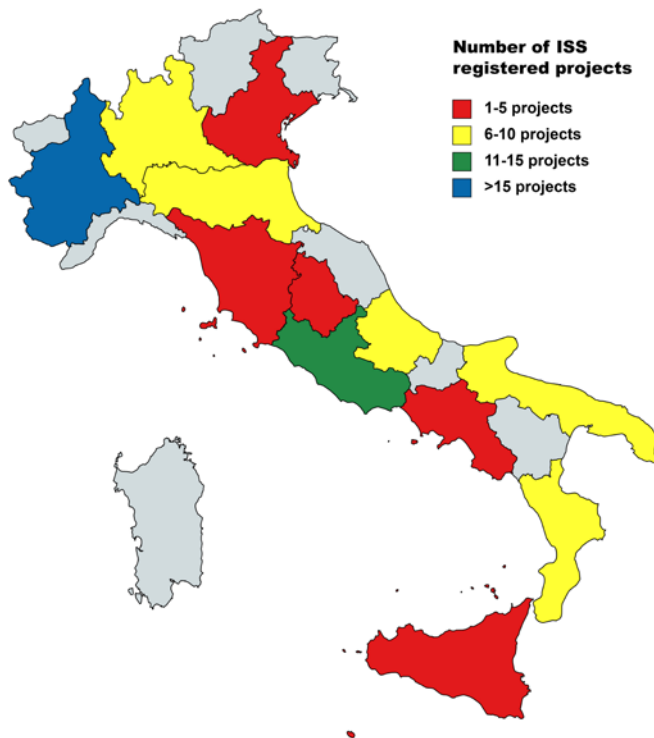
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<sup>6</sup><https://bit.ly/3VzYynH>.

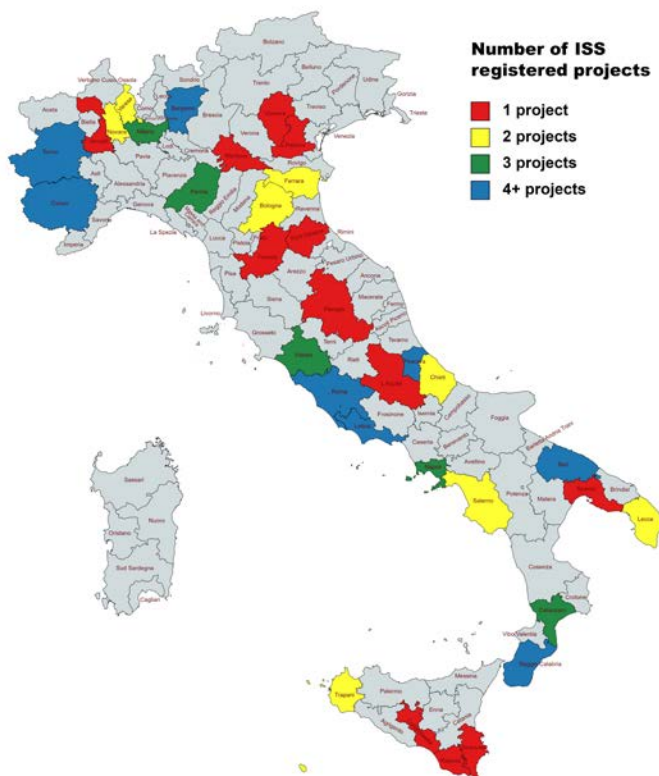
<sup>7</sup><https://bit.ly/3ChUsus>.

<sup>8</sup><https://bit.ly/3AfAmi6>.

<sup>9</sup><https://bit.ly/443wGNk>.

**Figure 5.** *The 2017 Italian Regional Map of the ISS Registered Projects*

Source: [www.mapchart.net/europe-detailed.html](http://www.mapchart.net/europe-detailed.html).

**Figure 6.** *The 2017 Italian Provincial Map of the ISS Registered Projects*

Source: [www.mapchart.net/italy.html](http://www.mapchart.net/italy.html).

**Table 1.** *Geographic Distribution of All the Projects Registered in the ISS Contest*

Region	Accepted projects	Proposing schools	Provinces
PIEDMONT	43 projects	7 schools	4 provinces
LAZIO	13 projects	8 schools	3 provinces
LOMBARDY	10 projects	6 schools	4 provinces
CALABRIA	8 projects	5 schools	2 provinces
EMILIA-ROMAGNA	8 projects	4 schools	4 provinces
APULIA	7 projects	6 schools	3 provinces
ABRUZZO	7 projects	5 schools	3 provinces
CAMPANIA	5 projects	5 schools	2 provinces
SICILY	5 projects	4 schools	4 provinces
VENETO	2 projects	2 schools	2 provinces
TUSCANY	1 project	1 school	1 province
UMBRIA	1 project	1 school	1 province

Source: <https://bit.ly/3ChUsus>.

### *The Assessment of the ISS Projects in summer 2017*

The seven members of the *ISS* evaluation committee (3 from MDI, 3 from MIUR, and a scientist as President) monitored the compliance with the rules and the merit criteria, i.e., "innovativeness, creativity and executive simplicity of the project, interdisciplinary interest, inclusion in curricula, originality of the scientific and technological content, completeness of the descriptive documentation and of the artefact / prototype / application / experiment and/or procedures, repercussions and impact in real contexts, potential developments of the project" (translated from the MIUR Note No. 10475, Attachment No.1, Italian website<sup>10</sup>). Let us rank in order of score the best 17 projects, out of 110 accepted submissions, selected during Summer 2017 (translated from the MIUR list, Italian website<sup>11</sup>):

1. 4.8 points: *GEM PBR nutrients and oxygen in space*  
Design of a machine for cultivating in microgravity some cyanobacteria able to exploit waste products.
2. 4.7 points: *Space surveyor*  
Design of a small module with a remote control system replacing the ISS astronauts during their external inspections.
3. 3.8 points: *Fitness in space: portable technology solutions*  
Training protocol using biomedical devices to ensure a correct state of health and longer time in space.
4. 3.8 points (ex-aequo): *Big brother in outer space*  
Immersive virtual reality reproducing the effects on astronauts of life in space and weightlessness.
5. 3.7 points: *Space to your breakfast*  
Study on bringing the Mediterranean breakfast aboard the Space Station.

<sup>10</sup><https://bit.ly/3vy0PW4>.

<sup>11</sup><https://bit.ly/3vst3kX>.

6. 3.7 points (ex-aequo): *Environmental energy signature*  
Study about energy consumption and polluting emissions in comparison with the astronaut's environment.
7. 3.6 points: *Space Oddity*  
Design of a thermal mug to be used on the ISS.
8. 3.6 points (ex-aequo): *AE Space Herbs*  
Prototype to carry out hydroponic and aeroponic crops in the Space Station usable also in extreme terrestrial environments.
9. 3.5 points: *Drop Universe*  
Study of the behavior of drops of various liquids on different materials.
10. 3.2 points: *CRAYFIS ISS*  
Use of CRAYFIS (Cosmic RAYs Found In Smartphones) to be installed on smartphones on board the ISS.
11. 3.1 points: *Philae and Rover Exomars conquering the deep space*  
Realization of a 1:1 scale copy of Philae and Rover Exomars integrated by an app for the remote control of the two prototypes, with particular attention to the transmission of long-distance signals (time lag).
12. 3.1 points (ex-aequo): *Yoga in space*  
Yoga exercises for ameliorating the astronauts' psychophysical well-being.
13. 3.0 points: *ISS app*  
Application allowing any user to get in touch with an ISS astronaut.
14. 2.9 points: *The dice of daily life*  
Devise a game helping the community on the ISS to choose shareable values.
15. 2.8 points: *Gravitational rings*  
Verify an innovative type of elastic that allows exercises on board the ISS maintaining muscle mass and tone.
16. 2.3 points: *Project Scenedesmus*  
Studying the adaptations to different environmental conditions of some algal strains (in extraterrestrial conditions or within space bases). Similar technologies could be used on Earth in extreme environments.
17. 2.1 points: *Green Thumb*  
Cultivating some elements of the Mediterranean diet in space to improve cultivation techniques on Earth and ensure a quality diet for astronauts.

#### *The Announcement of the ISS Winners in Fall 2017*

On November 3, 2017, the MIUR announced the victory of seventeen projects selected by the ISS evaluation committee<sup>12</sup>; whose technology readiness level (recalling the ISO 16290:2013 standard) ranged from TRL 2 (formulation of technological applications) to TRL 5 (technology validation in relevant environment). We catalogue them by distinguishing the first place (Table 2), the second place (Table 3), and the third place (Table 4). All the projects submitted for the Area No. 4 "Observe the Earth to guard it" were ruled out and no projects classified in the

<sup>12</sup><https://bit.ly/3CsSU0G>.

third place for the Area No. 6 "Robots, satellites and astronauts conquering the Universe".

**Table 2.** *The First-Placed Projects of the ISS Contest for Italian Schools*

Area	Title	School	City (Region)
1	<i>Space to your breakfast</i>	"Salvo D'Acquisto"	Bracciano (Lazio)
2	<i>Fitness in space: portable technology solutions</i>	"Attilio Castelli"	Saronno (Lombardy)
3	<i>GEM PBR nutrients and oxygen in space</i>	"Donatelli-Pascal"	Milan (Lombardy)
5	<i>Big brother in outer space.</i>	"Peano-Pellico"	Cuneo (Piedmont)
6	<i>Space surveyor</i>	"Augusto Righi"	Taranto (Apulia)
7	<i>AE Space Herbs</i>	"Enrico Fermi"	Mantua (Lombardy)

Source: <https://bit.ly/3c62Pij>.

**Table 3.** *The Second-Placed Projects of the ISS Contest for Italian Schools*

Area	Title	School	City (Region)
1	<i>Space Oddity</i>	"Giacomo Chilesotti"	Thiene (Veneto)
2	<i>Yoga in space</i>	"Donatelli-Pascal"	Milan (Lombardy)
3	<i>Drop Universe</i>	"Corradino D'Ascanio"	Montesilvano (Abruzzo)
5	<i>Environmental energy signature</i>	"Pitagora"	Pozzuoli (Campania)
6	<i>Philae and Rover Exomars conquering the deep space</i>	"Pietro Paleocapa"	Bergamo (Lombardy)
7	<i>Project Scenedesmus</i>	"Don Lorenzo Milani"	Romano di Lombardia (Lombardy)

Source: <https://bit.ly/3c62Pij>.

**Table 4.** *The Third-Placed Projects of the ISS Contest for Italian Schools*

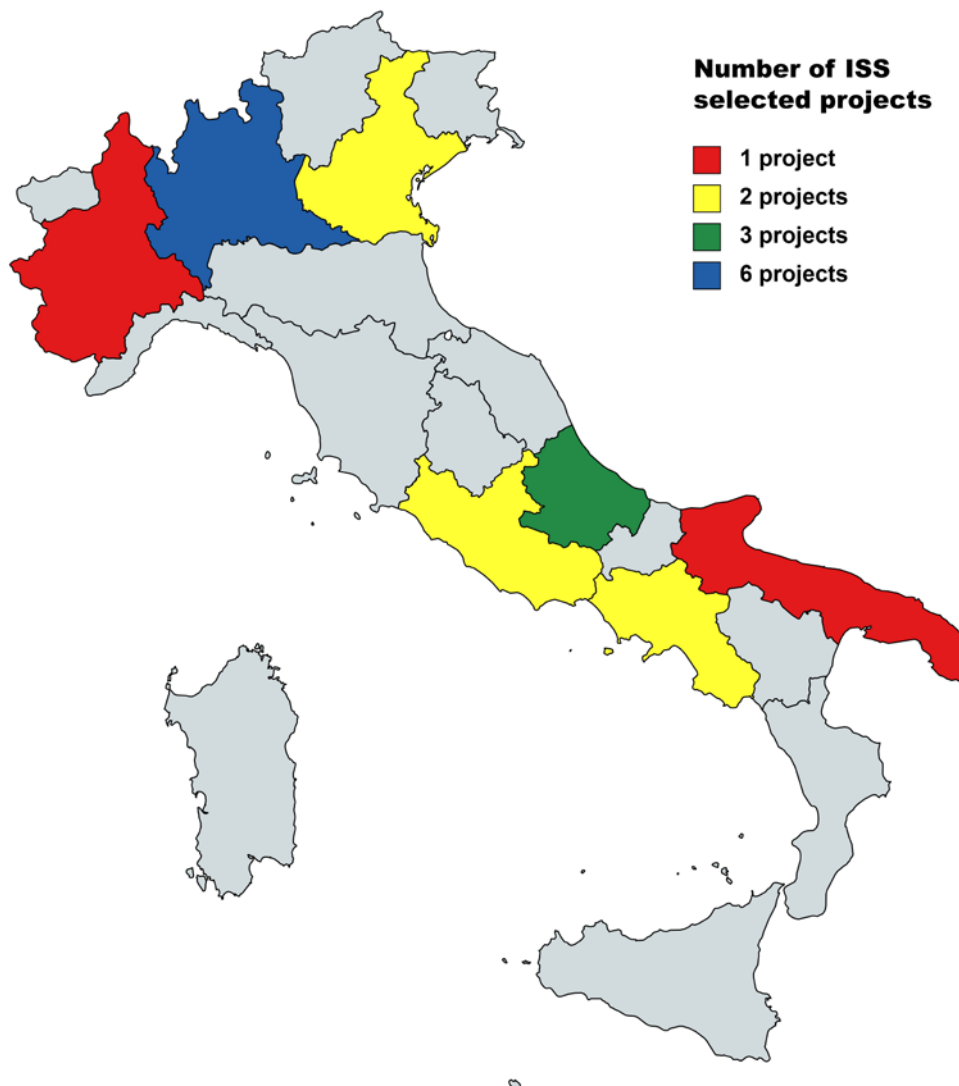
Area	Title	School	City (Region)
1	<i>The dice of daily life</i>	"Umberto Pomilio"	Chieti (Abruzzo)
2	<i>Gravitational rings</i>	"Patini-Liberatore"	Castel di Sangro (Abruzzo)
3	<i>CRAYFIS ISS</i>	"Leon Battista Alberti"	Abano Terme (Veneto)
5	<i>ISS app</i>	"Antonio Meucci"	Ronciglione (Lazio)
7	<i>Green Thumb</i>	"Publio Virgilio Marone"	Meta (Campania)

Source: <https://bit.ly/3c62Pij>.

From Tables 2–4 we can visualize the regional distribution of the selected schools on the Italian territory as follows (Table 5 and Figure 7).

**Table 5.** *Geographic Distribution of the Italian Schools Winning the ISS Contest*

Region	First place	Second place	Third place
LOMBARDY	3 projects	3 projects	-----
LAZIO	1 project	-----	1 project
APULIA	1 project	-----	-----
PIEDMONT	1 project	-----	-----
ABRUZZO	-----	1 project	2 projects
CAMPANIA	-----	1 project	1 project
VENETO	-----	1 project	1 project

**Figure 7.** The 2017 Italian Regional Map of the ISS Winning Projects

Source: [www.mapchart.net/europe-detailed.html](http://www.mapchart.net/europe-detailed.html).

The peaks of performance in the most productive parts of Italy, such as the whole Lombardy region and the industrial zone of Taranto, confirm that both STEM career knowledge and interests are influenced by society at large (Blotnick et al., 2018) and benefit from the partnerships with industry (Nistor et al., 2018) and multi-stakeholders (Jiménez-Iglesias et al., 2016). MIUR embraced the synergy of all these factors when introducing the: "technical tutorship a further element of originality of the initiative consists in the provision of a tutorship mechanism for the participating schools by third parties with specific skills in the fields contemplated by the call for applications, such as research centres, industries, universities, etc. On the one hand, this collaboration will offer enrichment opportunities for schools according to the *learning by doing* and *skills-based teaching* methodology, and on the other hand it will create local synergies, combining *production* and *training*. Thus, starting from November 2016 and up to

March 2017, the preliminary projects will be developed and implemented with the tutoring of one or more partners (company, authority, foundation, institution, industrial district, etc.) identified among the suitable subjects of the area and indicated in the preliminary project. The schools can activate contacts with the subjects indicated above autonomously or during in-depth workshops. The responsibility for identifying, assessing, and accepting the third-party partnership is up to the participating school." (Translated from the MIUR Note No. 10475, Italian website<sup>13</sup>).

#### *The ISS Awarding Ceremony in winter 2018*

On March 14, 2018, the winning schools were awarded at the auditorium of the Maxxi Museum in Rome. The event was attended by the Deputy Chief of Staff of the Ministry of Defense (Brigadier General Maurizio Cantiello), the Head of the 5th Department of the Air Force General Staff (Division General Giorgio Baldacci), and representatives of the Italian Space Agency and Thales Alenia Space. Cosmonaut Lieutenant Colonel Walter Villadei presented the works on behalf of the Selection Committee (ASI TV<sup>14</sup>). The celebration, introduced by the scientific communicator of Rai Cultura, Davide Coero Borga, was also attended by the Italian Minister of Education, University and Research, Valeria Fedeli, who declared: "Dear students, dear all, I am particularly happy to be here today for the awards ceremony of the national competition *School: space for your future. The ISS: Innovatio, Scientia, Sapientia*, which the Ministry of Education, University and Research promoted together with the Ministry of Defense and in collaboration with the Italian Space Agency. I am glad not only because we reward the ideas, talent, and intelligence of the new generations, but also because this competition was an extraordinary occasion of knowledge, of *school beyond school*, which gave the opportunity to female and male students to deepen the internal mechanisms of research, work, and future sectors. And they did so thanks to the support of experts, who have put their skills and professionalism at the service of young people. I want to thank all those who have been partners of this initiative: universities, research institutes, private companies, associations. Synergy in education is essential if we want to offer the girls and boys who attend our institutes opportunities for free and healthy growth. Why did we want a contest like this? A competition prompting female and male students to make proposals that could even be considered by ASI among the activities that will take place on board the International Space Station (ISS). Through this competition we wanted to contribute to the cultural growth and training of the younger generations, strengthening their knowledge and skills in the scientific and engineering disciplines; increase the interest of the school community for space and aerospace research; generate synergies and initiatives capable of increasing Italian participation, in the future, in a highly technological and rapidly expanding sector. The young participants – to whom I address my compliments – were able to challenge themselves by confronting and developing scientific and technological

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<sup>13</sup><https://bit.ly/3Pv0haY>.

<sup>14</sup><https://bit.ly/3KfOMDo>.

experimentation projects within seven thematic areas: from daily life to Space; train like an astronaut; test the Sciences in Space; observe the Earth to guard it; stay connected with an astronaut; robots, satellites and astronauts conquering the Universe; cultivate in space to cultivate better on Earth. Original and very interesting proposals have arrived: from the proposal of exercises to improve the psycho-physical health of astronauts through yoga to the study of how to bring the Mediterranean breakfast into space on board the Space Station. Or, ulteriorly, from the application allowing any user to get in touch with an astronaut on the International Space Station to the project that plans to cultivate some of the elements making up the Mediterranean diet in space to improve cultivation techniques on Earth and ensure astronauts a quality food diet. Today we reward these ideas, these works, the result of research, study, and in-depth analysis. But, at the same time, we break down a barrier, we put in communication worlds that may appear distant but are not (and must not be). We tell the new generations that any experience, even the most imaginative one, requires commitment, study, work and in some cases even sacrifice. That any profession, especially one of such great responsibility, requires solid skills and knowledge. Which are the inextinguishable thirst for knowledge and the determination to constantly test ourselves to take us into tomorrow, in the future, as in space. Space is marking, and increasingly will, the rhythm of our social and economic life. We have to look at this as a *system of systems*, based on the integration of different structures, technologies, and services, both *terrestrial* – traditionally understood – and typical of space programs. Our aim is to transform the European space sector into one of the driving forces for growth. We must see it as an engine and integrator of technological innovation processes in society as a whole. We must remember the great contribution that Space can make in the formation of the new generations by stimulating them to undertake a scientific career and letting them grow a strong sense of European identity. Only in this way our young people will be the protagonists of the new economic, political, and anthropological balances that are taking shape today. Paolo Nespoli, an astronaut with invaluable experience, recently returned from the VITA mission, has said: *"Being an astronaut on a rocket that is about to leave is like sitting on a mini atomic bomb that is about to explode in a controlled way and then if all goes well it throws you into space"*. Dealing with a space mission is anything but simple. It is a task requiring study. But it is also, at the same time, an important chance for progress and development. From today to the next 10 years the panorama will change, showing us new scientific and technological challenges, with further repercussions for Europe. It is an opportunity we cannot miss: we can grow, and we can do it together, thanks to the contribution of all those involved in this process. The exploration of space is an experience serving as an example and a reference, both practical and metaphorical, to express that need to discover, that curiosity to investigate that drive to go into the unknown to make it familiar. Isn't it, perhaps, the basis of knowledge and wisdom in general? The desire to overcome limits and boundaries, to cross new terrains different from their usual ones and to assume different perspectives, if not diametrically opposed, to the traditional ones? What brought us into Space is the same drive to learn that makes knowledge grow, that motivates us to study, that moves the world towards new



horizons. A push that is not only stemming from an irrational and uncontrolled impulse but is rather the result of a study and an in-depth analysis, that are essential conditions for approaching unknown realities. Dear girls and boys, take this cognitive experience with you, put it to good use. Keep it as track of each of your studies, professional and life paths. There are no boundaries that you cannot cross if you commit yourself, if you have the strength to believe in your dreams, if you have the courage to put yourself to the test. You have proved it to yourself thanks to this contest. We are with you." (Translated from the Letter of the Minister Fedeli to the *ISS* winners, Italian website<sup>15</sup>).

### *The Aftermath*

Up to date, none of the seventeen *ISS* winning projects appears on the "Complete list of the Italian microgravity experiments" (ASI website<sup>16</sup>). It seems implausible that secondary schools' proposals could be pondered, even just as basic insight, for being "subsequently developed and engineered, according to the necessary requirements, for experimentation in space flight" (translated from the MIUR Note No. 10475). Although missing its highest remuneration, the *ISS* stepped a milestone in the history of Italian Education; the spontaneous response from 12 regions (out of 20) and 33 provinces (out of 107) induced the Italian Ministry of Education to continue promoting Astronomy in STEM classrooms<sup>17</sup> by signing collaborations with:

- the Italian Astronomical Society (SAIt), aimed at disseminating the scientific culture and the sky sciences at school (April 9, 2021<sup>18</sup>);
- the European Space Agency (ESA), oriented to space-based innovation and digitalization for the school of tomorrow (June 21, 2021<sup>19</sup>).

In addition, the mentoring role was institutionalized on December 22, 2022<sup>20</sup>, by assigning a *Tutor* to each class group; this novel student assistance plan<sup>21</sup> corroborates the long tradition of *inclusivity* of the Italian school (Ianes et al. 2020).

### *Educational Impact*

The "Space for Your Future" was universally perceived as a rare incentive to contrast the low attractiveness of STEM studies (Nistor et al., 2018) through the STEM best practices (Sanders, 2012). In fact, all the presented projects were accomplished via PBL & PrBL (Barron et al., 1998) and boosted the IBSE

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<sup>15</sup><https://bit.ly/3Pzw1Mg>.

<sup>16</sup><https://bit.ly/3R59LL7>.

<sup>17</sup><https://bit.ly/3Hr7FSF>.

<sup>18</sup><https://bit.ly/3HISryo>.

<sup>19</sup><https://bit.ly/3wTVkBH>.

<sup>20</sup><https://bit.ly/3qKn9x0>.

<sup>21</sup><https://bit.ly/3qILfZ3>.

(Muciaccia et al., 2019), the ESD (Gras-Velázquez & Fronza, 2020) and, in many cases, the EDP (Hafiz & Ayop, 2019) and the ICT (Gras-Velázquez, 2016, 2017). Eventually, the "Innovatio, Scientia, Sapientia" contributed to reduce the gender gap in Science for secondary students (Makarova et al., 2019), to activate the emotional intelligence (Parker et al., 2004), and to reinforce the use of Science Laboratories (Hofstein & Mamlok-Naaman, 2007), eminently the Chemistry Lab (Hofstein, 2004). The entire ISS experience and the two-fold contribution from the "G.B. Grassi" of Latina, the scientific high school hosting the Planetarium "Livio Gratton" (Bonacci, 2011a), raised a genuine interest in the Section "Didactics of Physics" of the 104th Congress of the Italian Physical Society (September 17–21, 2018) at the University of Calabria – UniCal (Bonacci, 2018a) and in the Theme "BE a citizEn Scientist (BEES)" of the 13th European Researchers' Night (September 28, 2018) by Frascati Scienza (Bonacci, 2018b). The latter was the keynote lecture of "The Museum communicates and demonstrates Science", a citizen science meeting held at the "Museo della Terra Pontina"<sup>22</sup> (translatable as "Museum of the Pontine Land"), in the city of Latina (Miltiadis, 2020), and based on classroom works (Nistor et al., 2019).

### The ISS Educational Project by the "G.B. Grassi" High School

We focus on the educational project "Space for your Future. The ISS: Innovatio, Scientia Sapientia" by which the Scientific High School "Giovanni Battista Grassi" of Latina participated in the homonymous call for applications proposed by the Ministries of Education and Defense in the years 2016–2017. The Province of Latina has a distinct agricultural propensity, with the largest number of farm workers in the Lazio region (slightly higher than Rome)<sup>23</sup>. Latina is also the second province (next to Milan) for number of employees in pharma companies, and the first for pharmaceutical exports (ahead of Milan)<sup>24</sup>. The initiative was sponsored in Latina by the cosmonaut Walter Villadei who convinced the author, as Director of the Planetarium "Livio Gratton" (Bonacci, 2013), to participate with an *ad hoc* project based on *constructivism*. Starting from October 2016, ten last-year pupils were divided into two groups of five (Team A & B) who developed the following experiences to be tested in space:

- A. "Chemical transformations with precipitate formation",
- B. "Redox reaction of colored reagents".

In both cases, the goal was the same: spotting the differences between the terrestrial and the space (micro-g) environment about the evolution of a low technology readiness level (TRL 4) chemical reaction. Owing to the protracted duration of their reactions, Teams A & B excluded ground-based drop facilities,

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<sup>22</sup><https://bit.ly/3RKTtIX>.

<sup>23</sup><https://bit.ly/3Hwnskw>.

<sup>24</sup><https://bit.ly/3jbez6v>.

like the *Einstein-Elevator*<sup>25</sup>, and any other experimental setup for domestic microgravity alternative to the International Space Station.

### *Project's Steps*

The school activity developed through the following phases:

1. September 2016: the School Council approved the *ISS* project presented by the author, who nominated Francesco Giuliano, Provincial Head of the International Year of Astronomy (IYA09) and of Chemistry (IYA11), as technical tutor for his curriculum of skilled chemist (Giuliano, 2008), appreciated teacher (Giuliano, 2011), and fine pedagogist (Giuliano, 2015).
2. October 2016: the author selected 10 motivated pupils who familiarized themselves with the updated regulation of the competition, studying the *ISS* as the home of humanity in space, and the significant contribution Italy gave to its construction (ASI website<sup>26</sup>).
3. October 2016 – November 2016: the students chose the III thematic area "Test the Sciences in Space", absorbing the concept of microgravity<sup>27</sup> and contriving two germinal projects (here identified as *ISS-A* and *ISS-B*).
4. November 7, 2016: the Principal Giovanna Bellardini sent the preliminary projects *ISS-A* and *ISS-B* to MIUR by registered mail.
5. November 2016 – January 2017: the pilot projects were refined via *learning by doing* (Dewey, 1916) in the Chemistry Lab (TRL 4).
6. January 2017 – March 2017: the experimental proposals were engineered through PBL & PrBL (Zhou et al., 2011) and EDP (Lin et al., 2021).
7. March 21, 2017: the definitive projects *ISS-A* and *ISS-B* were submitted to the Directorate General for the Regulations and Evaluation of the National Education System of MIUR (Bonacci et al., 2017a, 2017b).

They obtained a "moral victory", for being amid the few teams able to send their *final* results in time. In fact, the deadline for the submission was unexpectedly prolonged from March 31 to May 31, 2017.

### *Project's Targets*

STEM-focused activities require at least two different subjects (Kelley & Knowles, 2016), in our case: Chemistry and Astronomy. They are both curricular in the Italian schools, so there was no need for any special training. The *ISS* project studied simple chemical transformations, in aqueous system, validated in lab (technology level TRL 4); precisely, the calcium carbonate precipitation and the oxidation-reduction between copper sulfate and iron. The pupils used common substances, easily available and not harmful, noting down their physical properties and preparing the relative solutions in distilled water, whose concentrations were

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<sup>25</sup><https://bit.ly/3p0Xqzl>.

<sup>26</sup><https://bit.ly/3R8SmS4>.

<sup>27</sup><https://bit.ly/3xSkukD>.

defined in the execution phase. Appendixes A and B provide additional details about the experimental tests.

### *Project's Strategies*

The project manager and the technical tutor adopted the constructivist methodology (Piaget, 1954) letting the high schoolers develop organization and problem-solving abilities. For each test, the students annotated their observations in forms drawn up under the teachers' guidance. These forms were also prepared for the astronauts who, in the event of victory of one or both the proposed projects, would have compiled them with the experimental results obtained in the *micro-g* environment.

### *Project's Achievements*

The ISS educational project contributed to reach the benchmarks of STEM readiness (Mattern et al., 2015), improving the STEM competences (Boon Ng, 2019) beyond the classic 4C skills (Triana et al., 2020). Both the Teams A and B practiced the PBL & PrBL (Smith et al., 2022) and the EDP (English & King, 2015) within a *learning by doing* pattern based on feeding the students' curiosity (Kowalski & Kowalski, 2015). Guided by two male supervisors, the brilliant performance of Team B (with four female members out of five) showed that the gender gap in STEM fields is not necessarily due to mismatching mentors, as conversely claimed by Kricorian et al. (2020) and by Bilgin et al. (2022a). Nine of the ten ISS high schoolers enrolled in a STEM faculty in Fall 2017; it was an impressive percentage compared to the average 25% of STEM graduated in OECD countries until then (OECD, 2017), albeit not representing a statistical sample. Besides, all the six ISS female pupils succeeded in a STEM major; a stunning performance compared, e.g., to the 26% of UK young women graduated in core STEM subjects in 2019<sup>28</sup>.

## **Didactical Summary**

The Italian schools' competition "Innovatio, Scientia, Sapientia" contained all the driving factors for implementing a STEM pedagogy of that *high-quality* pursued by the European Education Area (EEA)<sup>29</sup>, and confirmed *Astronomy* as a gateway science<sup>30</sup> that should be inserted in any school curriculum (Percy, 2005). By virtue of fully sustainable projects (Carroll et al., 2019) a broad spectrum of STEM skills<sup>31</sup> was covered: problem solving, creativity, critical analysis, teamwork, independent thinking, initiative, communication, and digital literacy. The ISS optimized the STEM good practices (Kasza & Slater, 2017), by means of:

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<sup>28</sup><https://bit.ly/3R8ISbC>.

<sup>29</sup><https://bit.ly/3L3Z7Vj>.

<sup>30</sup><https://bit.ly/3GYXTqF>.

<sup>31</sup><https://bit.ly/3ZgWW5D>.

the PBL & PrBL (Wilhelm et al., 2023), the IBSE (EUN, 2019), the ESD (Bilgin et al., 2022b), the EDP (Winarno et al., 2020), and the ICT (Lukychova et al., 2021). The feedback of several secondary schools, such as the "G.B. Grassi" of Latina (big city in Lazio), revealed the importance of using the Science Laboratories (Hofstein & Kind, 2012), and of nourishing the students' curiosity (Fetto, 2015), by activating their emotional intelligence (Petrides et al., 2004). In this perspective, the memorandums of understanding between MIUR and, respectively, SAIIt and ESA, are comforting leaps forward.

## Conclusions

This paper is aimed at bolstering the current European Schoolnet's debate on STEM education<sup>32</sup> and disseminating Educational Science, Innovation and Research in the wake of the erstwhile project DESIRE<sup>33</sup>. We have delineated the "Space for Your Future. The ISS: Innovatio, Scientia, Sapientia", a STEM enrichment activity inheriting the legacy of the SUCCESS contest by ESA<sup>34</sup>. The ISS was a space competition promoted by MIUR & MDI in the years 2016–2017 to select, after strict scrutiny, experiments suitable for the International Space Station. It was massively participated, with 110 proposals presented by 54 Italian secondary schools. From the complete list of the Italian microgravity experiments by ASI we infer that neither one of the 17 winning projects has been considered yet for testing on board the International Space Station. Nevertheless, the "Innovatio, Scientia, Sapientia" was a formidable stimulus for STEM tasks accomplished by teen students throughout Italy (TRL 2–5). Indeed, the collective effort to supply new ideas for space exploration involved at least another subject cognate to Astronomy, such as Mathematics, Physics, Chemistry, Biology etc. The correlation between the industrialization of a land and the positive response by territorial schools was confirmed in Latina, a manufacturing Italian province where the Scientific High School "Giovanni Battista Grassi" joined the ISS challenge with two teams. They participated through a *learning by doing* model (supremely via PBL & PrBL) leading to portable solutions in the field of Chemistry. Namely, they proposed to test in space a redox reaction of colored reagents and a chemical transformation with precipitate formation, each in an appropriately designed reaction vessel. The high schoolers accepted the "Space for Your Future" with enthusiasm also because, in fall 2016, the "G.B. Grassi" had already a consolidated experience of STEM projects and citizen science around its Planetarium "Livio Gratton". Other success factors were the availability of a well-equipped chemistry laboratory at school and the technical tutorship of Francesco Giuliano, an excellent constructivist teacher of Chemistry. Being among the few schools which submitted their results within the first deadline of March 31, 2017, the "G.B. Grassi" obtained a *moral victory* and its ISS projects were popularized in major conferences. Emerging as pivotal of superb STEM pedagogy, *Astronomy* should

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<sup>32</sup><https://bit.ly/3RfTqng>.

<sup>33</sup><https://bit.ly/3hXNwes>.

<sup>34</sup><https://bit.ly/3KfsPGc>.

be included in every school's curriculum as single subject or interdisciplinary course and a permanent partnering with national or international space agencies should become a priority of any institution meeting with the EEA's standards for a quality education. In our opinion, exemplary Stem & Space programs are *NAC*<sup>35</sup>, *EEE*<sup>36</sup>, *S4G*<sup>37</sup>, *MoCRiS*<sup>38</sup> for school pupils, and *Micro-g NExT*<sup>39</sup>, *DEPLOY!*<sup>40</sup>, *PETRI*<sup>41</sup> for undergraduates.

## Remarks

In 2020, the Italian Ministry of Education, University and Research (MIUR) split in two:

- 1) the Ministry of Education (MI)
- 2) the Ministry of University and Research (MUR)

The Italian Ministry of Education (MI), responsible for primary and secondary schools, further changed into the Ministry of Education and Merit (MIM) on November 4, 2022<sup>42</sup>.

## Acknowledgments

We are grateful to Francesco Giuliano for his voluntary participation as precious tutor in the *ISS* educational project by the Scientific High School "G.B. Grassi" of Latina. We also thank the anonymous reviewers for their helpful comments and valuable suggestions.

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<sup>35</sup><https://bit.ly/3qsU3l2>.

<sup>36</sup><https://bit.ly/43PprbS>.

<sup>37</sup><https://bit.ly/3Ct5LPf>.

<sup>38</sup><https://bit.ly/3qPNBVD>.

<sup>39</sup><https://go.nasa.gov/42Mn34J>.

<sup>40</sup><https://bit.ly/46eaO41>.

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## Appendix A – Precipitation Reaction

The Project ISS–A (Table 6) verifies the precipitation of calcium carbonate in *microgravity*, comparing it with the same reaction performed on Earth:  $\text{Ca(OH)}_2 (\text{aq}) + \text{CO}_2 (\text{g}) = \text{CaCO}_3 (\text{s}) + \text{H}_2\text{O} (\text{l})$ .

**Table 6.** The ISS Project A of the Scientific High School "G.B Grassi"

<b>Title</b>	Chemical transformations with formation of precipitate
<b>Reaction</b>	$\text{Ca(OH)}_2 (\text{aq}) + \text{CO}_2 (\text{g}) = \text{CaCO}_3 (\text{s}) + \text{H}_2\text{O} (\text{l})$
<b>Materials</b>	Mass $\text{Ca(OH)}_2$ : $m = 0.4 \text{ g}$ , Volume $\text{H}_2\text{O}$ : $V = 300 \text{ mL}$ ( $t = 20^\circ \text{ C}$ )
<b>Tools</b>	400 mL beaker, balance (sensitivity $0.01 \text{ g}$ ), thermometer, straw
<b>Area</b>	No. 3 "Test the Sciences in Space"
<b>Project Manager</b>	Enzo BONACCI, Teacher of Mathematics and Physics, Director of the Planetarium "Livio Gratton" in Latina
<b>Students</b>	Gabriele CALDARINI, Francesca Romana CALVI, Riccardo CATANIA, Simone CIOTTI, Alessandra DEL MONTE
<b>Project external Tutor</b>	Francesco GIULIANO, retired Teacher of Chemistry, former Lecturer of Chemistry Didactics at SSIS (School of Specialization in Secondary Teaching), Province Head of IYA09 & IYC11 in Latina

Source: <https://bit.ly/3B0zMq1>.

The Team A mixed 0.4 grams of calcium hydroxide in 300 milliliters of distilled water until it reached transparency in the beaker. After blowing into the straw (i.e., adding carbon dioxide), the solution became *opaque* in 2 minutes and 30 seconds. The solute *precipitated* completely in circa 8 hours (Fig. 8). Since the terminal velocity of a sphere falling in a fluid is directly proportional to the acceleration due to *gravity*, according to Stokes' law, the Team A wished the ISS crew to reply to the following question:

1. Will  $\text{CaCO}_3$  precipitate in space or will the solid remain suspended?

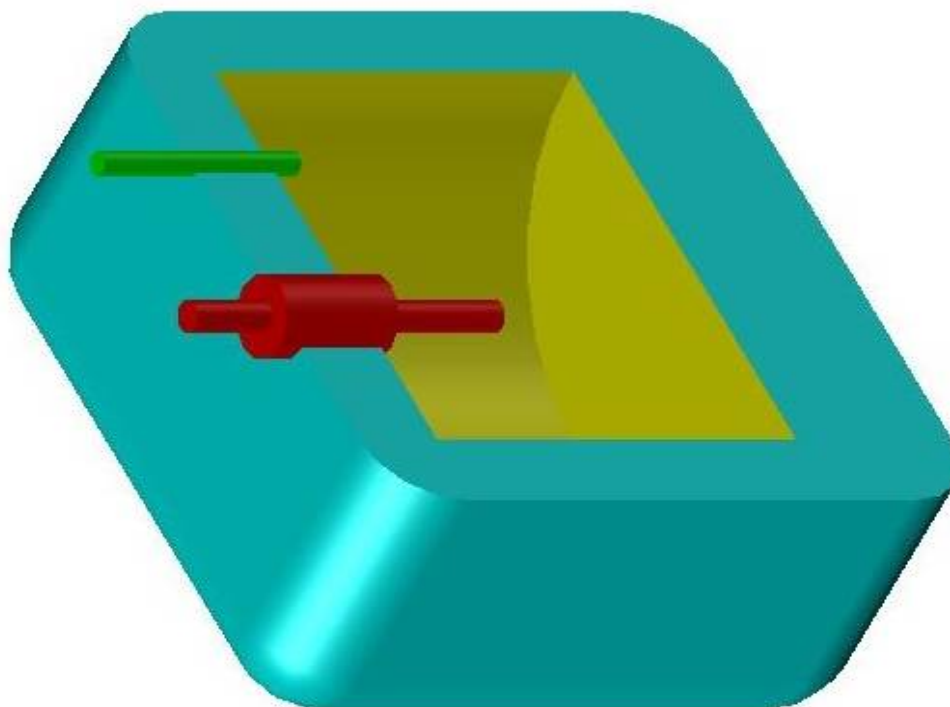
**Figure 8.** From the Opaque Solution to the Full Precipitation of  $\text{CaCO}_3$



Source: <https://bit.ly/3B0zMq1>.

The Team A excogitated a transparent, inert acrylic *reaction vessel* fitting the conditions aboard the International Space Station (Fig. 9), with a *red* flow valve and a *green* external/internal pressure balancing valve.

**Figure 9.** Front View of Team A's Vessel 3D Model



Source: <https://bit.ly/3B0zMq1>.

The ISS astronauts should blow on the mouthpiece of the *red* flow valve, measure the interval of time for an opaque solution and, if it happens, for the precipitation of  $\text{CaCO}_3$ ; next they should fill in the two missing entries in the following Table 7.

**Table 7.** The Astronauts' Form for the Project ISS-A

Test's data and results	Experiment on Earth	Experiment on the ISS
Volume of $\text{H}_2\text{O}$	300 mL (at $t=20^\circ\text{C}$ )	300 mL (at $t=20^\circ\text{C}$ )
Mass of $\text{Ca}(\text{OH})_2$	0.4 g	0.4 g
Solubility of $\text{Ca}(\text{OH})_2$	1.7 g/L (at $20^\circ\text{C}$ )	1.7 g/L (at $20^\circ\text{C}$ )
Time of opacification	2 minutes and 30 seconds	
Time of precipitation	8 hours	

Source: <https://bit.ly/3B0zMq1>.

The main merits of the *ISS-A* and *ISS-B* are a clear feasibility and a striking inventiveness, being projects never tried in ESA's educational activities<sup>43</sup> and programmes<sup>44</sup>.

<sup>43</sup><https://bit.ly/43xIskF>.

<sup>44</sup><https://bit.ly/43wFP1m>.

## Appendix B – Redox Reaction

The Project *ISS-B* (Table 8) verifies the oxidation-reduction between copper sulfate and iron in *microgravity*, comparing it with the same reaction performed on Earth:  $\text{Fe (s)} + \text{Cu}^{2+} \text{ (aq)} \rightarrow \text{Fe}^{2+} \text{ (aq)} + \text{Cu (s)}$ .

**Table 8.** *The ISS Project B of the Scientific High School "G.B Grassi"*

<b>Title</b>	Redox reaction of colored reagents
<b>Reaction</b>	$\text{Fe (s)} + \text{Cu}^{2+} \text{ (aq)} \rightarrow \text{Fe}^{2+} \text{ (aq)} + \text{Cu (s)}$
<b>Materials</b>	55 mL of $\text{H}_2\text{O}$ , 15.8 g of $\text{CuSO}_4$ , 3.53 g of iron filings (Fe)
<b>Tools</b>	150 mL beaker, balance (sensitivity 0.01 g), thermometer
<b>Area</b>	No. 3 "Test the Sciences in Space"
<b>Project Manager</b>	Enzo BONACCI, Teacher of Mathematics and Physics, Director of the Planetarium "Livio Gratton" in Latina
<b>Students</b>	Giulia CHILLEMI, Federica MADDALONI, Alice PACINI, Gianluca SBANDI, Chiara TRUINI
<b>Project external Tutor</b>	Francesco GIULIANO, retired Teacher of Chemistry, former Lecturer of Chemistry Didactics at SSIS (School of Specialization in Secondary Teaching), Province Head of IYA09 & IYC11 in Latina

Source: <https://bit.ly/3B0zMq1>.

The Team B mixed, in the beaker, 15.8 grams of copper sulphate ( $\text{CuSO}_4$ ) in 55 milliliters of distilled water until it reached a *blue* color at  $18^\circ\text{C}$ . They add 3.53 grams of iron filings (Fe) and the solution became *dark grey*, turning *dark red* as copper precipitated (Fig. 10). After stirring, the *green* ferrous sulphate ( $\text{FeSO}_4$ ) formed in circa 4 minutes and the temperature reached  $33^\circ\text{C}$ . The Team B wished the ISS crew to answer to the following question:

1. Will the redox in space evolve in the same way as far as reaction time, product color, and temperature are concerned?

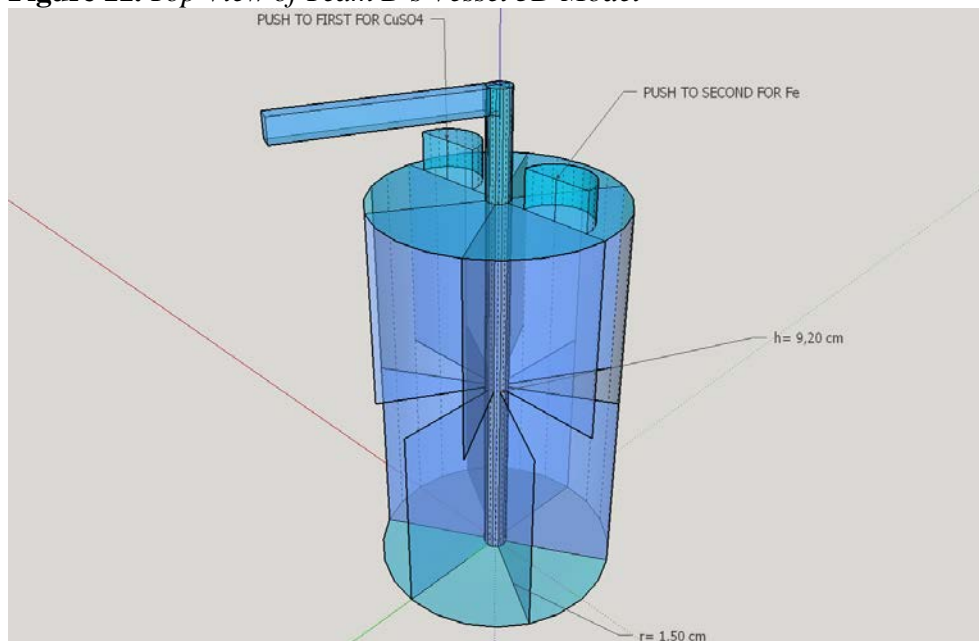
**Figure 10.** *Reaction Between  $\text{CuSO}_4$  and Fe Until the Formation of  $\text{FeSO}_4$*



Source: <https://bit.ly/3B0zMq1>.

The Team B devised a transparent, inert acrylic *reaction vessel* fitting the conditions aboard the International Space Station (Fig. 11), with two lateral buttons for introducing the copper sulphate (first push) and the iron filings (second push), and a central winged mixer.

**Figure 11.** Top View of Team B's Vessel 3D Model



Source: <https://bit.ly/3B0zMq1>.

The ISS astronauts are expected to push the  $CuSO_4$  button and fill the first two lines of the last column (Tab. 9). Then they should push the  $Fe$  button and fill the third and fourth lines of the form. They have to rotate the mixer, waiting for the  $FeSO_4$  formation, and complete the form. If measuring the temperature was too difficult on board the ISS, the empty cells (second and seventh lines) should be left blank.

**Table 9.** The Astronauts' Form for the Project ISS-B

Test's data and steps	Experiment on Earth	Experiment on the ISS
Color after adding $CuSO_4$ to water	Blue	
Initial temperature	18 °C	
Color soon after adding iron filings	Dark grey	
Color during copper's precipitation	Dark Red	
Color after mixing of reagents	Green	
Period of $FeSO_4$ formation	4 minutes	
Final temperature	33 °C	

Source: <https://bit.ly/3B0zMq1>.



## Anisotropic Strange Stars with Nonlinear Equation of State

By Manuel Malaver\*

*The modeling of superdense matter is an interesting research area and in the last decades, such models allow explain the behavior of massive objects as neutron stars, quasars, pulsars and white dwarfs. Taking local anisotropy into consideration, in this paper we present a new classes of solutions for the Einstein's field equations in a spherically symmetric spacetime under the influence of an electric field considering a quadratic equation of state with a particular form the metric potential that depends on an adjustable parameter. The obtained solutions can be written in terms of elementary functions, namely polynomials and algebraic functions. The graphs generated show that physical variables such as metric potentials, radial pressure, energy density, charge density, anisotropy, radial speed sound are consistent with realistic stellar models. The results of this research can be useful in the development and description of new models of compact structures.*

**Keywords:** *quadratic equation of state, Einstein-Maxwell system, metric potential, adjustable parameter, compact structures*

### Introduction

The search of new solutions for the Einstein-Maxwell field equations is an important area of research because it allows describe compact objects with strong gravitational fields as neutron stars, white dwarfs and quark stars (Bicak 2006, Kuhfitting 2011). Within this context it is appropriate to mention the findings of Delgaty and Lake (1998) who constructed several analytic solutions that can describe realistic stellar configurations and satisfy all the necessary conditions to be physically acceptable. These exact solutions have also made it possible the way to study cosmic censorship and analyze the formation of naked singularities (Joshi 1993).

In the development of the first stellar models it is important to mention the pioneering research of Schwarzschild (1916), Tolman (1939), Oppenheimer and Volkoff (1939) and Chandrasekhar (1931). Schwarzschild (1916) obtained interior solutions that allows describing a star with uniform density, Tolman generated new solutions for static spheres of fluid, Oppenheimer, and Volkoff (1939) studied the gravitational equilibrium of neutron stars using Tolman's solutions and Chandrasekhar (1931) produced new models of white dwarfs in presence of relativistic effects.

A great number of exact models from the Einstein-Maxwell field equations have been generated by Gupta and Maurya (2011), Kiess (2012), Mafa Takisa and Maharaj (2013), Malaver and Kasmaei (2020), Malaver (2017, 2018a), Ivanov

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(2002) and Sunzu et al. (2014). For the construction of these models, several forms of equations of state can be considered (Sunzu 2018). Komathiraj and Maharaj (2007), Malaver (2016), Bombaci (1997), Thirukkanesh and Maharaj (2008), Dey et al. (1998) and Usov (2004) assume linear equation of state for quark stars. Feroze and Siddiqui (2011) considered a quadratic equation of state for the matter distribution and specified particular forms for the gravitational potential and electric field intensity. Mafa Takisa and Maharaj (2013) obtained new exact solutions to the Einstein-Maxwell system of equations with a polytropic equation of state. Thirukkanesh and Ragel (2012) have obtained particular models of anisotropic fluids with polytropic equation of state which are consistent with the reported experimental observations. Malaver (2013) generated new exact solutions to the Einstein-Maxwell system considering Van der Waals modified equation of state with polytropic exponent. Malaver and Kasmaei (2020) proposed a new model of compact star with charged anisotropic matter using a cosmological Chaplygin fluid. Tello-Ortiz et al. (2020) found an anisotropic fluid sphere solution of the Einstein-Maxwell field equations with a modified Chaplygin equation of state. More recently, Malaver et al. (2022) obtained new solutions of Einstein's field equations in a Buchdahl spacetime considering a nonlinear electromagnetic field.

The analysis of compact objects with anisotropic matter distribution is very important, because that the anisotropy plays a significant role in the studies of relativistic spheres of fluid (Esculpi et al. 2007, Cosenza et al. 1982, Herrera 1992, Herrera and Nuñez 1989, Herrera et al. 1979, Herrera et al. 1984, Malaver 2014a, Malaver 2014b, Malaver 2014c, Malaver 2015, Malaver 2016, Malaver 2017, Malaver 2018a, Malaver 2018b, Malaver 2018c, Malaver 2018d, Sunzu and Danford 2017, Bowers and Liang 1974). Anisotropy is defined as  $\Delta = p_t - p_r$  where  $p_r$  is the radial pressure and  $p_t$  is the tangential pressure. The existence of solid core, presence of type 3A superfluid (Sokolov 1980), magnetic field, phase transitions, a pion condensation and electric field (Usov 2004) are most important reasonable facts that explain the presence of tangential pressures within a star. Many astrophysical objects as X-ray pulsar, Her X-1, 4U1820-30 and SAXJ1804.4-3658 have anisotropic pressures. Bowers and Liang (1974) include in the equation of hydrostatic equilibrium the case of local anisotropy. Bhar et al. (2015) have studied the behavior of relativistic objects with locally anisotropic matter distribution considering the Tolman VII form for the gravitational potential with a linear relation between the energy density and the radial pressure. Malaver (2015, 2018d), Feroze and Siddiqui (2011, 2014) and Sunzu et al. (2014) obtained solutions of the Einstein-Maxwell field equations for charged spherically symmetric spacetime by assuming anisotropic pressure.

In this paper we generated new classes of exact solutions for anisotropic charged distribution with a consistent with quark matter. New models have been obtained by specifying a particular form for one of the metric potentials and for the electric field intensity. The paper has been organized as follows: In section 2, we present the Einstein's field equations. In section 3, we have chosen a particular form for the metric potential and for the electric field intensity in order to obtain



the new models. In Section 4, physical requirements for the new models are described. In section 5, the models obtained are physically analyzed. In section 6, the conclusions of the work are presented.

### Einstein's Field Equations

We consider a spherically symmetric, static and homogeneous spacetime. In Schwarzschild coordinates the metric is given by:

$$ds^2 = -e^{2\nu(r)} dt^2 + e^{2\lambda(r)} dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2) \quad (1)$$

where  $\nu(r)$  and  $\lambda(r)$  are two arbitrary functions.

Using the transformations,  $x = Cr^2$ ,  $Z(x) = e^{-2\lambda(r)}$  and  $A^2 y^2(x) = e^{2\nu(r)}$  with arbitrary constants  $A$  and  $c > 0$ , suggested by Durgapal and Bannerji (1983), the Einstein-Maxwell field equations according to Feroze and Siddiqui (2011) can be written as:

$$\frac{1-Z}{x} - 2\dot{Z} = \frac{\rho}{C} + \frac{E^2}{2C} \quad (2)$$

$$4Z \frac{\dot{y}}{y} - \frac{1-Z}{x} = \frac{p_r}{C} - \frac{E^2}{2C} \quad (3)$$

$$p_t = p_r + \Delta \quad (4)$$

$$\frac{\Delta}{C} = 4xZ \frac{\ddot{y}}{y} + \dot{Z} \left( 1 + 2x \frac{\dot{y}}{y} \right) + \frac{1-Z}{x} - \frac{E^2}{C} \quad (5)$$

$$\sigma^2 = \frac{4CZ}{x} (x\dot{E} + E)^2 \quad (6)$$

$\rho$  is the energy density,  $p_r$  is the radial pressure,  $E$  is electric field intensity,  $p_t$  is the tangential pressure,  $\sigma$  is the charge density,  $\Delta = p_t - p_r$  is the measure of anisotropy and dots denote differentiations with respect to  $x$ .

With the transformations of Durgapal and Bannerji (1983), the mass within a radius  $r$  of the sphere take the form

$$M(x) = \frac{1}{4C^{3/2}} \int_0^x \sqrt{x} \rho(x) dx \quad (7)$$

In this paper, we assume the following quadratic equation of state

$$p_r = \alpha \rho^2 + \beta \rho \quad (8)$$

where  $\alpha, \beta$  are arbitrary constant.

### The New Anisotropic Models

With the Thirukanesh-Ragel-Malaver ansatz (Malaver 2014a, Horvath and Moraes 2020) we take the form for the metric potential  $Z(x)$ , which is well behaved and regular in the origin. The electric field intensity  $E$  is continuous in the interior and finite at the centre of the star. So for  $Z(x)$  and  $E$  we have

$$Z(x) = (1 - ax)^n \quad (9)$$

$$\frac{E^2}{2C} = \frac{ax}{(1 + ax)} \quad (10)$$

In equation (9)  $n$  is an adjustable parameter. In this paper, we considered the particular cases  $n=1, 2$ .

For the case  $n=1$ , with the equations (9) and (10) in eq. (2) we obtained for the energy density

$$\rho = C \left( \frac{3a(1 + ax) - ax}{1 + ax} \right) \quad (11)$$

Using eq. (11) in eq. (8) the radial pressure can be written as

$$p_r = \alpha C^2 \left( \frac{3a(1 + ax) - ax}{1 + ax} \right)^2 + \beta C \left( \frac{3a(1 + ax) - ax}{1 + ax} \right) \quad (12)$$

Substituting (12),  $Z(x)$  and eq. (10) in eq. (3) we have

$$\frac{\dot{y}}{y} = \frac{1}{4C(1 - ax)} \left[ \frac{\alpha C^2 (3a(1 + ax) - ax)^2}{(1 + ax)^2} + \frac{\beta C (3a(1 + ax) - ax)}{(1 + ax)} \right] + \frac{a}{4(1 - ax)} - \frac{ax}{4(1 - ax)(1 + ax)} \quad (13)$$

and integrating eq. (13)

$$y(x) = c_1 (ax - 1)^{A*} (ax + 1)^B e^{-\frac{C\alpha}{8a(ax+1)}} \quad (14)$$

where  $c_1$  is the constant of integration

For convenience we have let

$$A^* = \frac{-36a^2\alpha C^2 + 12a\alpha C^2 - 12a\beta C - \alpha C^2 - 4aC + 2\beta C + 2C}{16aC} \quad (15)$$

$$B = \frac{12a\alpha C - 3\alpha C + 2\beta + 2}{16a} \quad (16)$$

For the metric functions  $e^{2\lambda}$ ,  $e^{2\nu}$

$$e^{2\lambda} = \frac{1}{1-ax} \quad (17)$$

$$e^{2\nu} = A^2 c_1^2 (ax-1)^{2A^*} (ax+1)^{2B} e^{-\frac{C\alpha}{4a(ax+1)}} \quad (18)$$

and the anisotropy  $\Delta$  can be written as

$$\Delta = 4xC(1-ax) \left[ \frac{(A^2-A)a^2}{(ax-1)^2} + \frac{2Aa^2B}{(a^2x^2-1)} + \frac{AaC\alpha}{4(ax-1)(ax+1)^2} + \frac{(B^2-B)a^2}{(ax+1)^2} + \frac{Ba\alpha C - a\alpha C}{4(ax+1)^3} \right. \\ \left. + \frac{C^2\alpha^2}{64(ax+1)^4} \right] - a \left[ 1 + 2x \left( \frac{Aa}{ax-1} + \frac{Ba}{ax+1} + \frac{C\alpha}{8(ax+1)} \right) \right] + \frac{a+a^2x-2ax}{1+ax} \quad (19)$$

With  $n=2$ , the expression for the energy density is

$$\rho = C \left( \frac{6a + a^2x - 5a^3x^2 - ax}{1+ax} \right) \quad (20)$$

replacing eq. (20) in eq. (8), we have for the radial pressure

$$p_r = \alpha C^2 \left( \frac{6a + a^2x - 5a^3x^2 - ax}{1+ax} \right)^2 + \beta C \left( \frac{6a + a^2x - 5a^3x^2 - ax}{1+ax} \right) \quad (21)$$

Substituting eq. (21),  $Z(x)$  and eq. (10) in eq. (3) we obtain

$$\frac{\dot{y}}{y} = \frac{1}{4C(1-ax)^2} \left[ \frac{\alpha C^2(6a+a^2x-5a^3x^2-ax)^2}{(1+ax)^2} + \frac{\beta C(6a+a^2x-5a^3x^2-ax)}{(1+ax)} - \gamma \right] + \frac{2a-a^2x}{4(1-ax)^2} - \frac{ax}{4(1-ax)(1+ax)}$$

(22)

Integrating eq. (22) we have

$$y(x) = c_2 (ax-1)^{C*} (ax+1)^D e^{\frac{Ex^3+Fx+G}{8ac(ax+1)(ax-1)}} \quad (23)$$

where  $c_2$  is the constant of integration

Again for convenience

$$C^* = \frac{-40a^2\alpha C + 18a\alpha C - 20a\beta + \alpha C - 4a - \beta - 1}{16a} \quad (24)$$

$$D = \frac{22a\alpha C - \alpha C + \beta + 1}{16a} \quad \text{and} \quad E = 50a^5\alpha C^2 \quad (25)$$

$$F = -52a^3\alpha C^2 + 2a^2\alpha C^2 - 2a^2\beta C - a\alpha C^2 - 2a^2C + a\beta C + aC \quad (26)$$

$$G = -2a^2\alpha C^2 + 2a\alpha C^2 - 2a\beta C - 2ac + \beta C + C \quad (27)$$

and for the metric functions  $e^{2\lambda}$ ,  $e^{2\nu}$  and anisotropy  $\Delta$  we have

$$e^{2\lambda} = \frac{1}{(1-ax)^2} \quad (28)$$

$$e^{2\nu} = c_2^2 (ax-1)^{2C*} (ax+1)^{2D} e^{\frac{Ex^3+Fx+G}{4ac(ax+1)(ax-1)}} \quad (29)$$

$$\Delta = 4xC(1-ax) \left[ \begin{aligned} & \left( \frac{(C^*-C^*)a^2}{(ax-1)^2} + \frac{2a^2DC^*}{(a^2x^2-1)} + \frac{2aC^*}{ax-1} \left( \frac{3Ex^2+2Fx}{8aC(a^2x^2-1)} - \frac{Ex^3+Fx+G}{8C(ax+1)^2(ax-1)} \right) \right. \\ & \left. + \frac{(D^2-D)a^2}{(ax+1)^2} + \frac{Da}{ax+1} \left( \frac{3Ex^2+2Fx}{8aC(a^2x^2-1)} - \frac{Ex^3+Fx+G}{8C(ax+1)^2(ax-1)} - \frac{Ex^3+Fx+G}{8C(ax+1)(ax-1)^2} \right) \right. \\ & \left. + \frac{6Ex+2F}{8aC(a^2x^2-1)} - \frac{3Ex^2+2Fx}{4C(ax+1)^2(ax-1)} - \frac{3Ex^2+2Fx}{4C(ax+1)(ax-1)^2} + \frac{(Ex^3+Fx+G)a}{4C(ax+1)^3(ax-1)} \right. \\ & \left. + \frac{(Ex^3+Fx+G)a}{4C(ax+1)^2(ax-1)^2} + \frac{(Ex^3+Fx+G)a}{4C(ax+1)(ax-1)^3} + \left( \frac{3Ex^2+2Fx}{8aC(a^2x^2-1)} - \frac{Ex^3+Fx+G}{8C(ax+1)^2(ax-1)} \right)^2 \right. \\ & \left. - \frac{Ex^3+Fx+G}{8C(ax+1)(ax-1)^2} \right) \end{aligned} \right] \\ + 2aC - a^2Cx - \frac{2aCx}{1+ax} \quad (30)$$

### Conditions of the Physical Acceptability

0 For a model to be physically acceptable, the following conditions should be satisfied (Delgaty and Lake 1998, Malaver 2014a):

- (i) The metric potentials  $e^{2\lambda}$  and  $e^{2\nu}$  assume finite values throughout the stellar interior and are singularity-free at the center  $r=0$ .
- (ii) The energy density  $\rho$  should be positive and a decreasing function inside the star.
- (iii) The radial pressure also should be positive and a decreasing function of radial parameter.
- (iv) The radial pressure and density gradients  $\frac{dp_r}{dr} \leq 0$  and  $\frac{d\rho}{dr} \leq 0$  for  $0 \leq r \leq R$ .
- (v) The anisotropy is zero at the center  $r=0$ , i.e.  $\Delta(r=0) = 0$ .
- (vi) Any physically acceptable solution must satisfy the causality condition where the radial speed of sound  $v_{sr}^2$  should be less than speed of light throughout the model, i.e.,  $0 \leq v_{sr}^2 = \frac{dp_r}{d\rho} \leq 1$ .
- (vii) The interior solution should match with the exterior of the Reissner-Nordstrom spacetime, for which the metric is given by

$$ds^2 = -\left(1 - \frac{2M}{r} + \frac{Q^2}{r^2}\right) dt^2 + \left(1 - \frac{2M}{r} + \frac{Q^2}{r^2}\right)^{-1} dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \quad (31)$$

Through the boundary  $r=R$  where  $M$  and  $Q$  are the total mass and the total charge of the star, respectively.

The conditions (ii) and (iv) imply that the energy density must reach a maximum at the centre and decreasing towards the surface of the sphere.

### Physical Analysis of the New Models

With  $n=1$ , the metric potentials  $e^{2\lambda}$  and  $e^{2\nu}$  have finite values and remain positive throughout the stellar interior. At the center  $e^{2\lambda(0)} = 1$  and  $e^{2\nu(0)} = A^2 c_1^2 (-1)^{2A^*} e^{\frac{C\alpha}{4a}}$ . We show that in  $r=0$   $(e^{2\lambda(r)})'_{r=0} = (e^{2\nu(r)})'_{r=0} = 0$  and this makes is possible to verify that the gravitational potentials are regular at the center. The energy density and radial pressure are positive and well behaved between the center and the surface of the star. In the center  $\rho(r=0) = 3aC$  and  $p_r(r=0) = 9a^2 \alpha C^2 + 3\beta Ca - \gamma$ ,

therefore the energy density will be non-negative in  $r=0$  and  $p_r(r=0) > 0$ . In the surface of the star  $r=R$  and we have  $p_r(r=R)=0$  and  $R = \frac{3}{\sqrt{3C-9aC}}$ . For the radial pressure and density gradients we obtain

$$\frac{d\rho}{dr} = \frac{C^2(6a^2r-2ar)}{1+aCr^2} - \frac{2arC^2[3a(1+aCr^2)-aCr^2]}{(1+aCr^2)^2} \quad (32)$$

$$\begin{aligned} \frac{dp_r}{dr} = & \frac{2\alpha C^2[3a(1+aCr^2)-aCr^2][6a^2-2a]Cr}{(1+aCr^2)^2} - \frac{4\alpha C^3[3a(1+aCr^2)-aCr^2]^2 ar}{(1+aCr^2)^3} \\ & - \frac{\beta C(6a^2Cr-2aCr)}{1+aCr^2} + \frac{2\beta C^2[3a(1+aCr^2)-aCr^2]ar}{(1+aCr^2)^2} \end{aligned} \quad (33)$$

In order to maintain of causality, the radial sound speed should be within the limit  $0 \leq v_{sr}^2 \leq 1$  in the interior of the star (Delgaty and Lake 1998, Herrera 1992). In this model, we have:

$$0 \leq v_{sr}^2 = \frac{dp_r}{d\rho} = 2\alpha C \frac{[3a(1+aCr^2)-aCr^2]}{(1+aCr^2)} + \beta \leq 1 \quad (34)$$

On the boundary  $r=R$ , the solution must match the Reissner–Nordström exterior space–time as

$$ds^2 = -\left(1 - \frac{2M}{r} + \frac{Q^2}{r^2}\right) dt^2 + \left(1 - \frac{2M}{r} + \frac{Q^2}{r^2}\right)^{-1} dr^2 + r^2(d\theta^2 + \sin^2\theta d\varphi^2) \quad (35)$$

and therefore, the continuity of  $e^{2\lambda}$  and  $e^{2\nu}$  across the boundary  $r=R$  is

$$e^{2\nu} = e^{2\lambda} = 1 - \frac{2M}{R} + \frac{Q^2}{R^2} \quad (36)$$

Then for the matching conditions, we obtain:

$$\frac{2M}{R} = \frac{(a^2 + 2a)C^2R^4 + aCR^2}{1+aCR^2} \quad (37)$$

For the case  $n=2$ , we have for the metric potentials  $e^{2\lambda(0)}=1$ ,  $e^{2\nu(0)}=A^2 C^2 (-1)^{2C^*} e^{-\frac{G}{4aC}}$  and  $(e^{2\lambda(r)})'_{r=0} = (e^{2\nu(r)})'_{r=0} = 0$  at the centre  $r=0$ . Again the gravitational potentials are regular in the origin. The energy density and radial pressure also are positive and well behaved in the stellar interior. In the center  $\rho(r=0) = 6aC$  and  $p_r = 36\alpha a^2 C^2 + 6a\beta C$ , therefore the energy density will be non-negative in  $r=0$  and  $p_r(r=0) > 0$ . In the surface of the star  $r=R$  and we have  $p_r(r=R)=0$  and  $R = \frac{\sqrt{10C(a-1+\sqrt{121a^2-2a+1})}}{10aC}$ . For the radial pressure and density gradients we obtain

$$\frac{d\rho}{dr} = C \left( \frac{-20C^2 a^3 r^3 + 2Ca^2 r - 2Car}{1 + aCr^2} \right) - 2C^2 ar \left( \frac{-5C^2 a^3 r^4 + Ca^2 r^2 - Car^2 + 6a}{(1 + aCr^2)^2} \right) \quad (38)$$

$$\begin{aligned} \frac{dp_r}{dr} = & \frac{2\alpha C^2 [-5C^2 a^3 r^4 + Ca^2 r^2 - aCr^2 + 6a] - 20C^2 a^3 r^3 + 2Ca^2 r - 2Car}{(1 + aCr^2)^2} \\ & - \frac{4\alpha C^3 [-5C^2 a^3 r^4 + Ca^2 r^2 - aCr^2 + 6a]^2 ar}{(1 + aCr^2)^3} - \frac{\beta C (-20C^2 a^3 r^3 + 2Ca^2 r - 2Car)}{1 + aCr^2} \quad (39) \\ & + \frac{2\beta C^2 (-5C^2 a^3 r^4 + Ca^2 r^2 - Car^2 + 6a) ar}{(1 + aCr^2)^2} \end{aligned}$$

The causality condition implies that

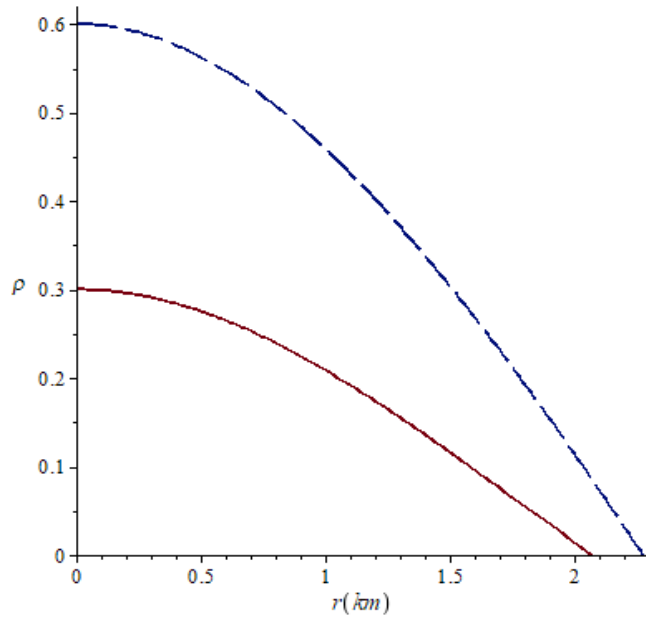
$$0 \leq 2\alpha C \left( \frac{6a + a^2 Cr^2 - 5a^3 C^2 r^4 - acr^2}{1 + aCr^2} \right) + \beta \leq 1 \quad (40)$$

On the boundary  $r=R$ , the solution must match the Reissner–Nordström exterior space–time and therefore for the matching conditions, we obtain:

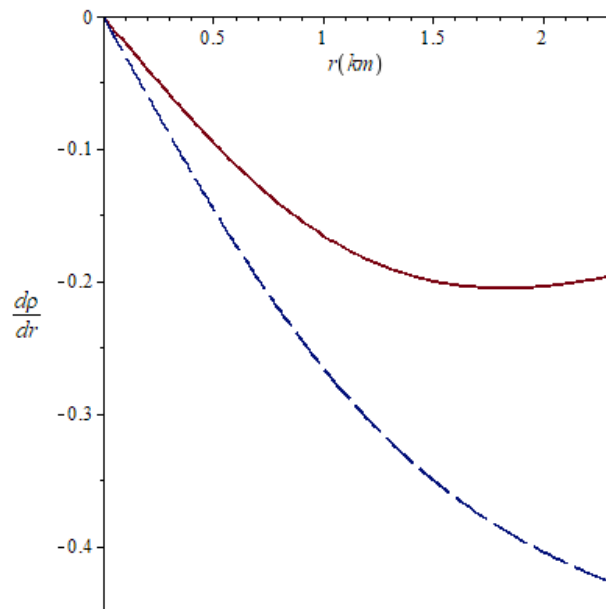
$$\frac{2M}{R} = \frac{aCR^2 + (a^2 + 2a)C^2 R^4 - a^3 C^3 R^6}{1 + aCR^2} \quad (41)$$

Figures 1, 2, 3, 4, 5 and 6 present the dependence of  $\rho$ ,  $\frac{d\rho}{dr}$ ,  $p_r$ ,  $\frac{dp_r}{dr}$ ,  $v_{sr}^2$  and  $\Delta$  with the radial coordinate respectively with  $a=0.1$ ,  $\alpha=0.25$ ,  $\beta=0.5$ ,  $C=1$  for  $n=1$  and  $n=2$ .

**Figure 1.** Energy Density against Radial Coordinate. It has been Considered that  $n=1$ (Solid Line);  $n=2$  (Long-Dash Line)

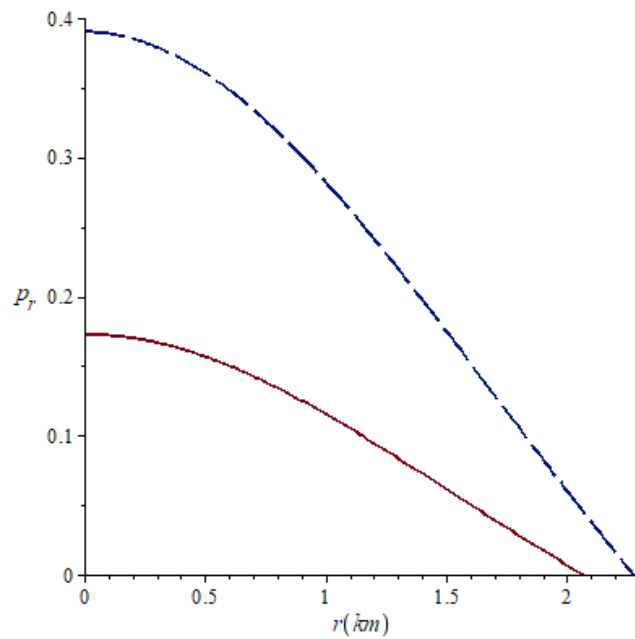


**Figure 2.** Density Gradient against Radial Coordinate. It has been Considered that  $n=1$ (Solid Line);  $n=2$  (Long-Dash Line)

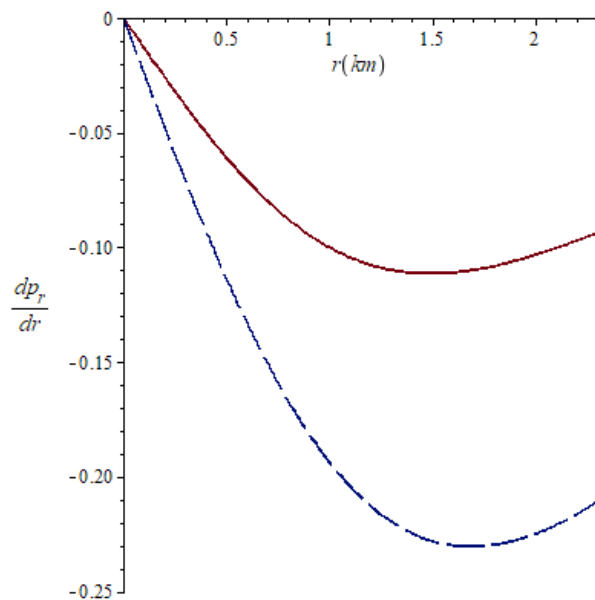




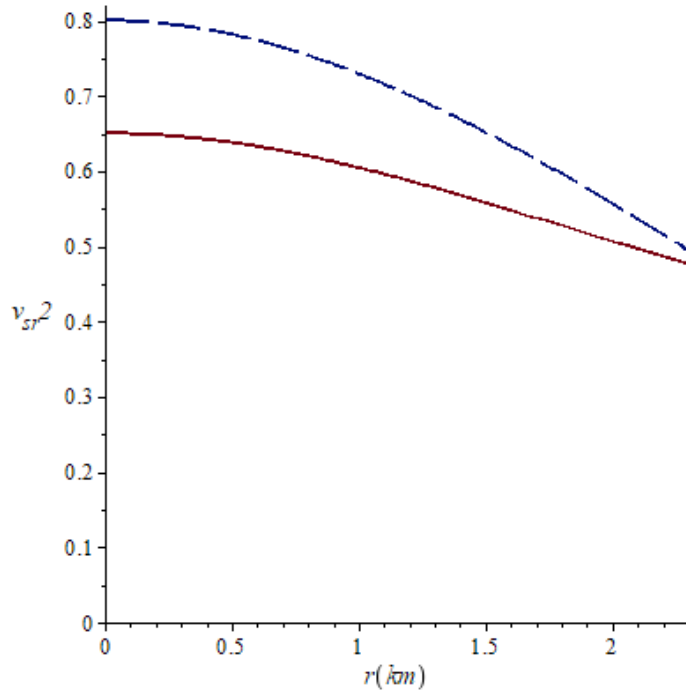
**Figure 3.** Radial Pressure against Radial Coordinate. It has been Considered that  $n=1$ (Solid Line);  $n=2$  (Long-Dash Line)



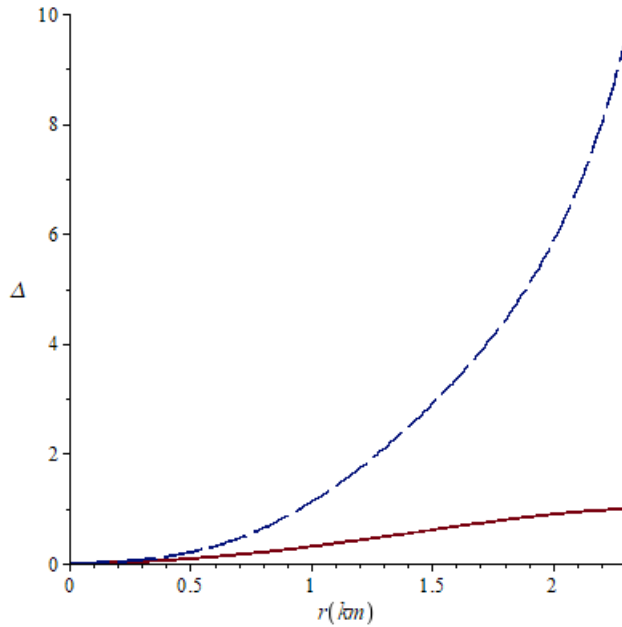
**Figure 4.** Radial Pressure Gradient against Radial Coordinate. It has been Considered that  $n=1$ (Solid Line);  $n=2$  (Long-Dash Line)



**Figure 5.** The Radial Speed of Sound against Radial Coordinate. It has been Considered that  $n=1$ (Solid Line);  $n=2$  (Long-Dash Line)



**Figure 6.** Anisotropy against Radial Coordinate. It has been Considered that  $n=1$ (Solid Line);  $n=2$  (Long-Dash Line)



In Figure 1 is shown that the energy density remains positive, continuous and is monotonically decreasing function throughout the stellar interior. In Figure 2 it is noted that for the radial variation of energy density gradient  $\frac{d\rho}{dr} < 0$  in the two

cases studied. The radial pressure showed the same behavior by the energy density, that is, it is growing within the star and vanishes at a greater radial distance and its results are shown in Figure 3. The presence of a quadratic term in the equation of state causes an increase in the maximum values. Again, according to Figure 4, the profile of  $\frac{dp_r}{dr}$  shows that radial pressure gradient is negative inside the star for  $n=1$  and  $n=2$ . Figure 5 shows that the condition  $0 \leq v_{sr}^2 \leq 1$  is maintained throughout the interior of the star and satisfy the causality, which is a physical requirement for the construction of a realistic star (Joshi 1993). The anisotropic factor is plotted in Figure 6 and it shows that vanishes at the centre of the star, i.e.,  $\Delta(r=0) = 0$  (Delgaty and Lake 1998).

## Conclusions

In this paper we have generated new models of anisotropic stars considering the Thirukkanesh-Ragel-Malaver ansatz for the gravitational potential and a quadratic equation of state. These models may be used in the description of compact objects in absence of charge and in the study of internal structure of strange quark stars. We show that the developed configuration obeys the physical conditions required for the physical viability of the stellar model. The radial pressure, energy density, anisotropy and all the metric coefficients are regular at the origin and well behaved in the stellar interior.

The constants  $\alpha$  and  $\beta$  have been chosen in order to maintain the causality condition and the regularity of metric potentials inside the radius of the star. The new solutions match smoothly with the Reissner–Nordström exterior metric at the boundary  $r=R$ , because matter variables and the gravitational potentials of this work are consistent with the physical analysis of these stars. It is expected that the results of this research can contribute to modeling of relativistic compact objects and configurations with anisotropic matter distribution.

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