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CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

Saverio Bartalini

14C SCAR

Spettroscopia laser ad altissima sensibilità (SCAR): tecnologia abilitante alla certificazione di massa del contenuto biogenico di prodotti petroliferi

INNOVHUB STAZIONI SPERIMENTALI PER L'INDUSTRIA

UNICHIM

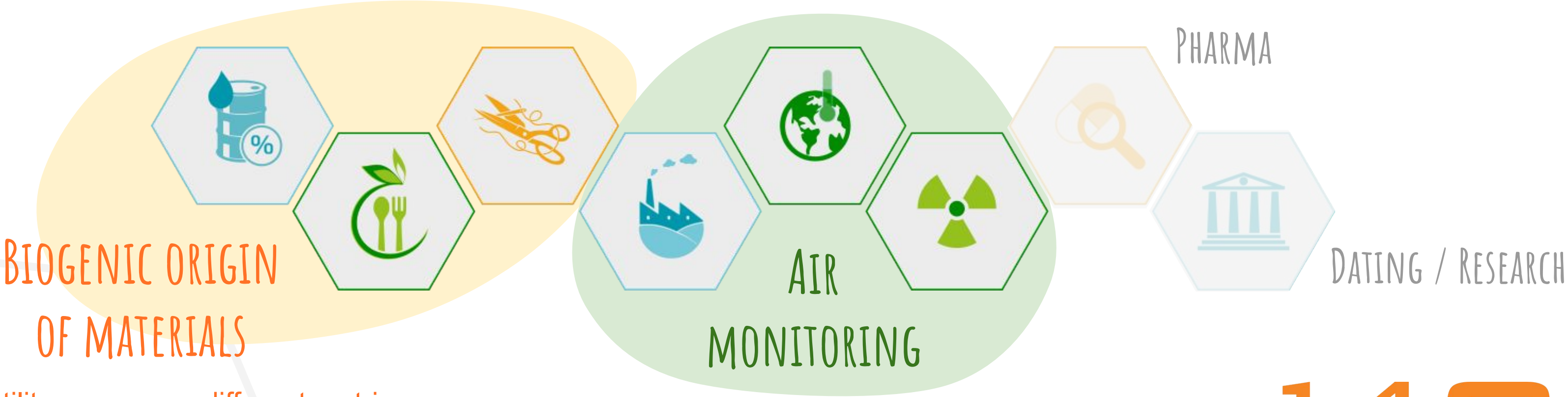
Radiocarbon in the Environment: an increasing demand of radiocarbon analyses

Delivering the European Green Deal

European Commission

Making Europe the first climate neutral continent in the world is our goal.

These proposals aim to make all sectors of the EU's economy fit to meet this challenge. They set the EU on a path to reach its climate targets by 2030 in a fair, cost effective and competitive way.



Versatility over many different matrices
Short result turnover
Easy deployability
Low costs

Continuous uninterrupted operation
On-field deployability
Low maintenance

14C SCAR

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Novità normative EU - Italia

DECRETO LEGISLATIVO 9 gennaio 2026, n. 5

Attuazione della direttiva (UE) 2023/2413 del Parlamento europeo e del Consiglio, del 18 ottobre 2023, che modifica la direttiva (UE) 2018/2001, il regolamento (UE) 2018/1999 e la direttiva n. 98/70/CE per quanto riguarda la promozione dell'energia da fonti rinnovabili e che abroga la direttiva (UE) 2015/652 del Consiglio. (26G00018)

note: Entrata in vigore del provvedimento: 04/02/2026

1. LA STRATEGIA (Il Quadro Generale Europeo)

[Documento]	[Funzione]	[Natura]
Direttiva (UE) 2023/2413 (Aggiornamento direttiva RED II)	Detta la visione politica. Fissa gli obiettivi vincolanti generali per la promozione dell'energia da fonti rinnovabili in tutta l'Unione Europea.	Richiede che i singoli Stati membri creino leggi nazionali per raggiungere questi scopi.

Da "oggi"

2. L'ATTUAZIONE (La Legge Nazionale Italiana)

[Documento]	[Funzione]	[Natura]
Decreto Legislativo 9 gennaio 2026, n. 5	È la traduzione in Italia della Direttiva Europea. Fissa gli obblighi legali e i target quantitativi italiani (ad esempio, il raggiungimento del 39,4% di energia da fonti rinnovabili nei consumi finali entro il 2030).	Regolamenta il mercato interno, obbligando i fornitori a immettere specifiche quote di biocarburanti.

Definizione delle metodologie di calcolo

3. LA REGOLA TECNICA (Il Manuale Operativo per le Industrie)

[Documento]	[Funzione]	[Natura]
Regolamento delegato (UE) 2023/1640	Risponde a un'esigenza pratica. Stabilisce l'esatta metodologia scientifica e di audit (imponendo l'uso del metodo del radiocarbonio 14C) per calcolare la vera quota bio nei carburanti derivati dal co-trattamento in raffineria (biomassa mescolata a fossile).	È una norma "scolpita nella pietra", direttamente e immediatamente applicabile in tutta Europa senza bisogno di decreti di recepimento.

REGOLAMENTO DELEGATO (UE) 2023/1640 DELLA COMMISSIONE del 5 giugno 2023

Sulla **metodologia** per determinare la quota di biocarburanti e di biogas per il trasporto derivanti da biomassa trattata con combustibili fossili in un processo comune.

L 205/2 | IT | Gazzetta ufficiale dell'Unione europea | 18.8.2023

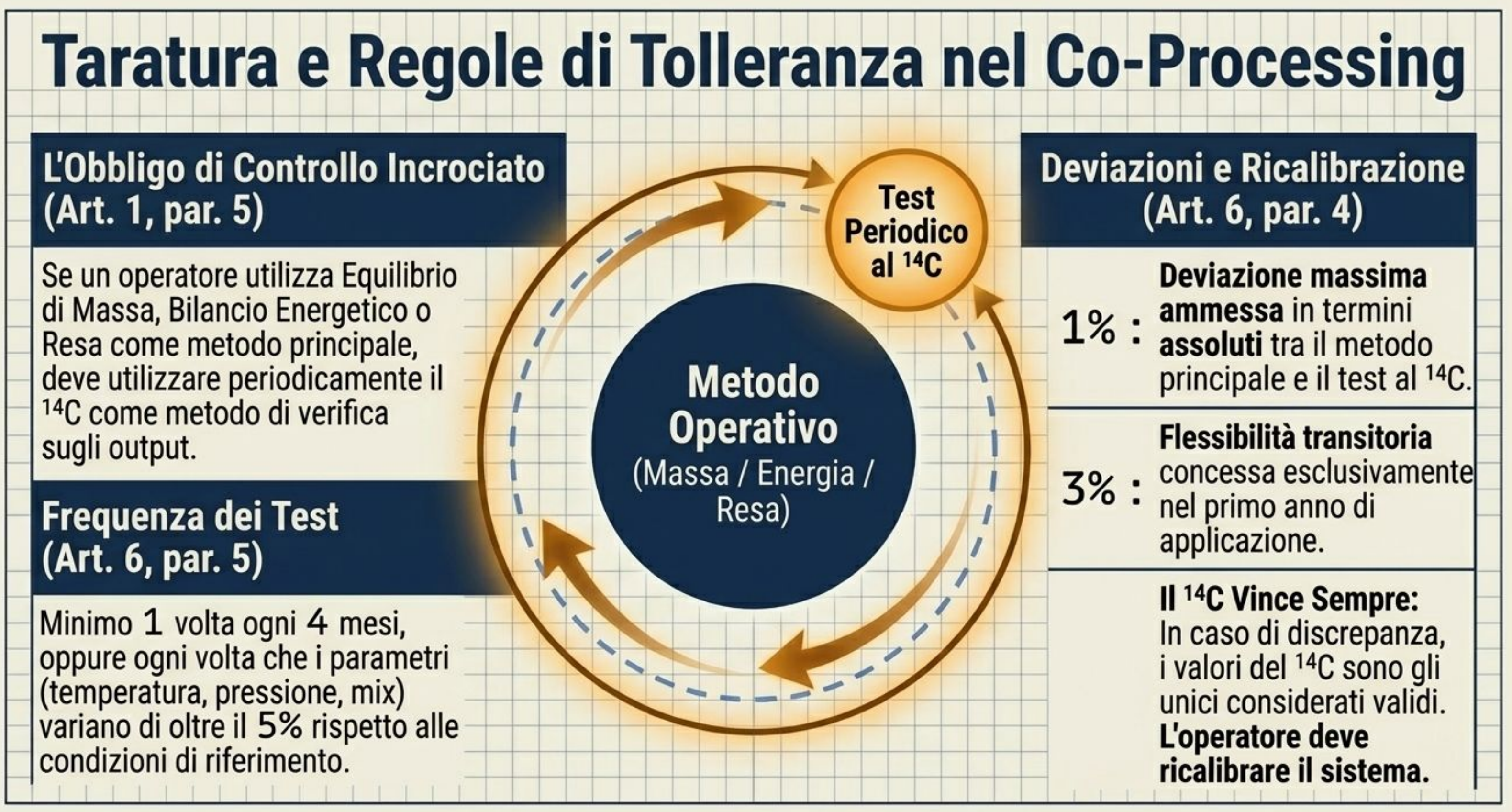
CAPO I

METODI PER DETERMINARE LA QUOTA DI BIOCARBURANTI E DI BIOGAS PER IL TRASPORTO DERIVANTI DA BIOMASSA TRATTATA CON I COMBUSTIBILI FOSSILI IN UN PROCESSO COMUNE

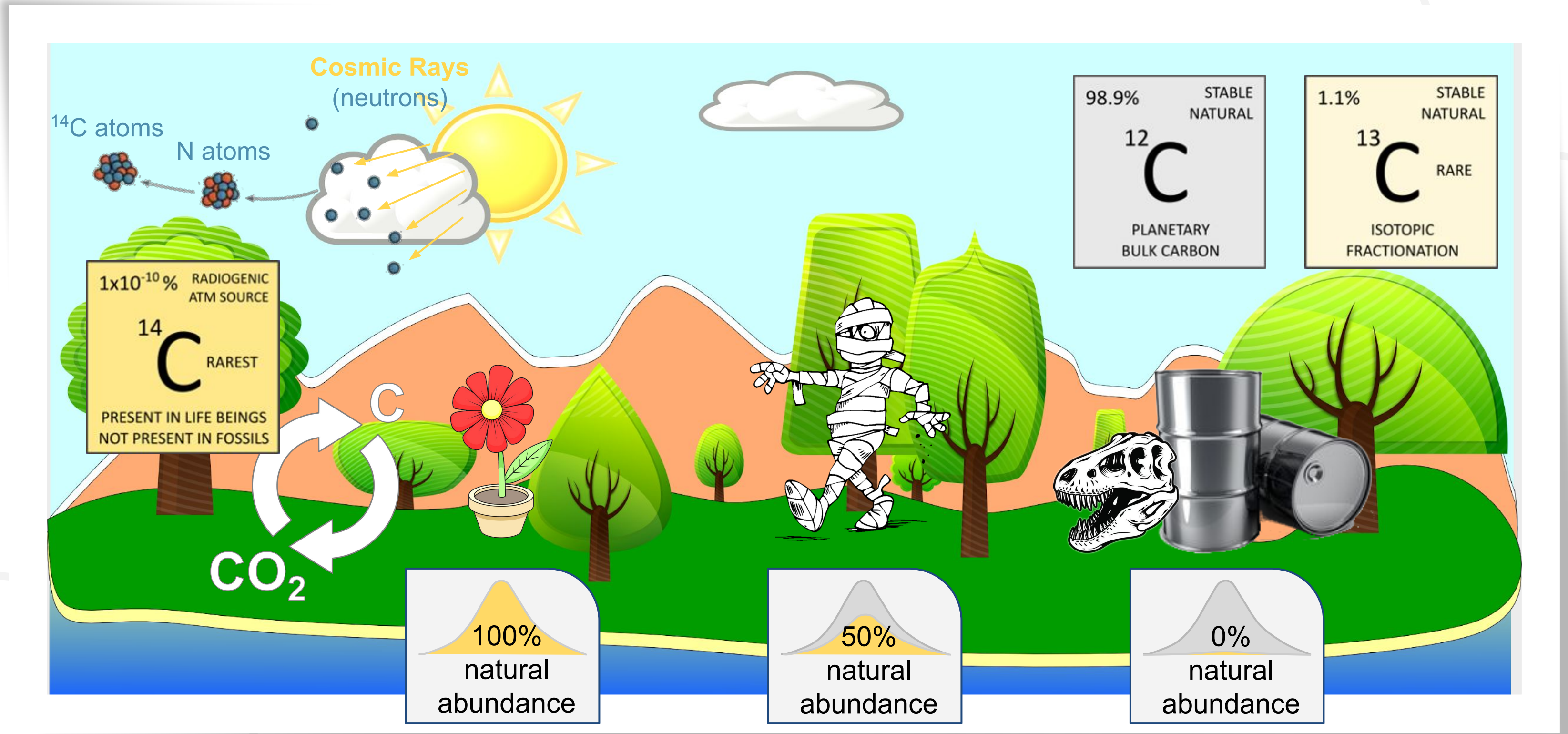
“Per trovare un equilibrio tra i costi di verifica e la precisione delle prove, l’atto delegato consente agli operatori economici di usare un **metodo di prova armonizzato comune basato sul radiocarbonio (14C), o di usare metodi di prova propri**, caratteristici dell’impresa o del processo. Tuttavia, per garantire l’applicazione di un metodo di prova comune sul mercato, **gli operatori economici il cui metodo principale è diverso da quello del radiocarbonio dovrebbero applicare periodicamente quest’ultimo** agli output per verificare la correttezza del metodo principale.
Inoltre, per consentire agli operatori economici di **abituarsi a usare il metodo del radiocarbonio** insieme a un altro metodo di prova principale, nel primo anno di applicazione di questa metodologia è previsto un certo grado di flessibilità… “

Metodologia	Principio Fondamentale	Caratteristiche Operative
Equilibrio di Massa	Input Massa = Output Massa	Sottrae umidità e impurità. Applica fattori di conversione ai prodotti considerando le perdite di processo.
Bilancio Energetico	Input Energia = Output Energia	Basato sul Potere Calorifico Inferiore (PCI). La frazione energetica biogenica in ingresso è applicata uniformemente a tutti gli output.
Resa (Metodo A / B)	Correlazione Input / Output	Confronta il rendimento solo fossile con quello misto. Richiede condizioni operative strettamente costanti e controllate.
Radiocarbonio (^{14}C)	Rilevazione Isotopica Diretta	Misura direttamente le molecole. Usato come metodo principale o come verifica obbligatoria per calibrare gli altri tre metodi.

REGOLAMENTO DELEGATO (UE) 2023/1640 DELLA COMMISSIONE del 5 giugno 2023



Introducing radiocarbon (^{14}C): **the marker of life.**



Modern - Bio **Ancient** **Fossil**

Application Example: Measuring the radiocarbon content of a fuel (or plastic) allows to determine if it is produced from **fossil oil** or from **renewable biogenic source** material.

Riunione dei partecipanti alle attività r

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The challenge of measuring radiocarbon concentration

^{14}C
isotope
abund. 1×10^{-10} %

Detection of radiocarbon (^{14}C) is challenging, due to its extremely low concentration in nature.

- **100 pMC ~ 1.2 ppt**
- **1 pMC ~ 12 ppq**

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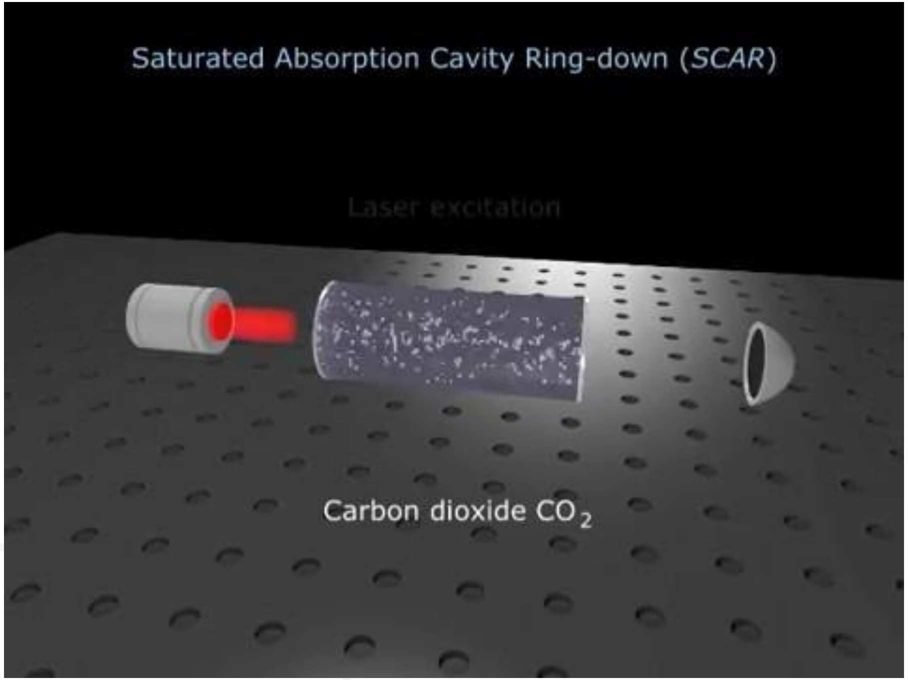
Saturated-absorption CAvity Ring-down (SCAR)



Patent WO2014170828A1, "Apparatus and method for measuring the concentration of trace gases by SCAR spectroscopy".

Patent WO2017055606A1, "Method for measuring the concentration of trace gases by SCAR spectroscopy"

Patent WO2016067241A1 ,"Low-noise current source"

PRL **104,** 110801 (2010) PHYSICAL REVIEW LETTERS week ending 19 MARCH 2010

Saturated-Absorption Cavity Ring-Down Spectroscopy

G. Giusfredi, S. Bartalini, S. Borri, P. Cancio, I. Galli, D. Mazzotti,* and P. De Natale
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(Received 14 October 2009; published 19 March 2010)

PRL **107,** 270802 (2011) PHYSICAL REVIEW LETTERS week ending 30 DECEMBER 2011

Molecular Gas Sensing Below Parts Per Trillion: Radiocarbon-Dioxide Optical Detection

I. Galli, S. Bartalini, S. Borri, P. Cancio,* D. Mazzotti, P. De Natale, and G. Giusfredi
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(Received 17 May 2011; published 30 December 2011)

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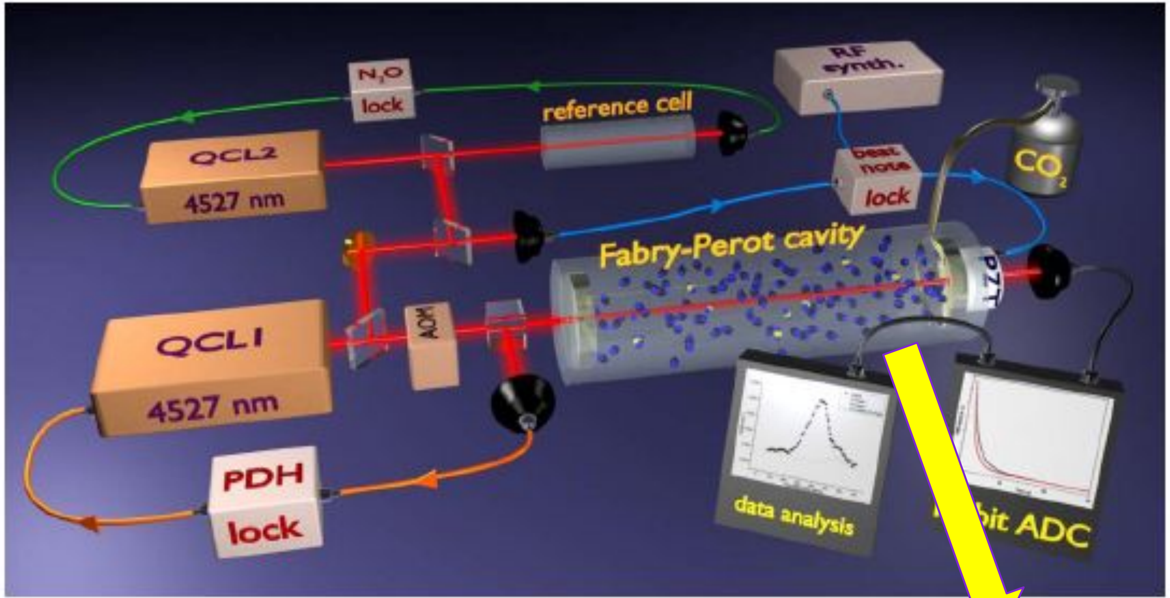
Spectroscopic detection of radiocarbon dioxide at parts-per-quadrillion sensitivity

IACOPO GALLI,[1,2] SAVERIO BARTALINI,[1,2] RICCARDO BALLERINI,[2] MARCO BARUCCI,[3] PABLO CANCIO,[1,2] MARCO DE PAS,[2] GIOVANNI GIUSFREDI,[1,2] DAVIDE MAZZOTTI,[1,2,*] NAOTA AKIKUSA,[4] AND PAOLO DE NATALE[1,2]

The concept of C14-SCAR



Achieved precision:

4 x 10^{-15}

parts

per

quadrillion

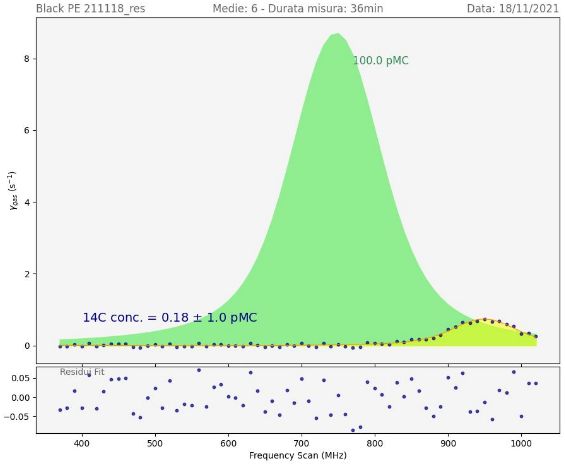
Quantum Cascade Lasers
Wavelength: 4.5 µm
Output power: 100 mW

High-finesse optical cavity
Length: 1 m Optical path: > 20 km
Cavity mode width: < 3 kHz

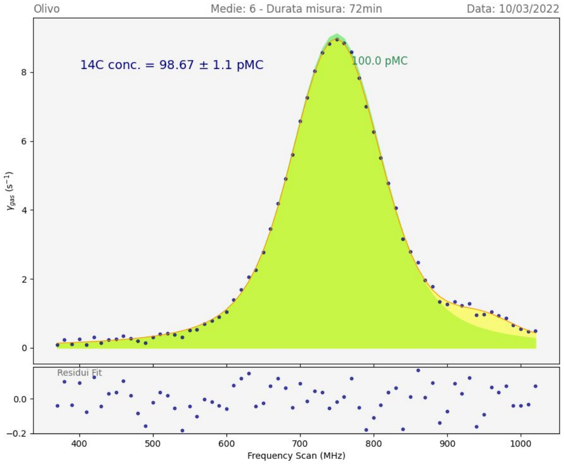
Measuring in the 0...1 Modern range, and beyond

The method is linear across a wide dynamic range: highly enriched samples (up to 1000 modern) can be measured without any significant memory effect.

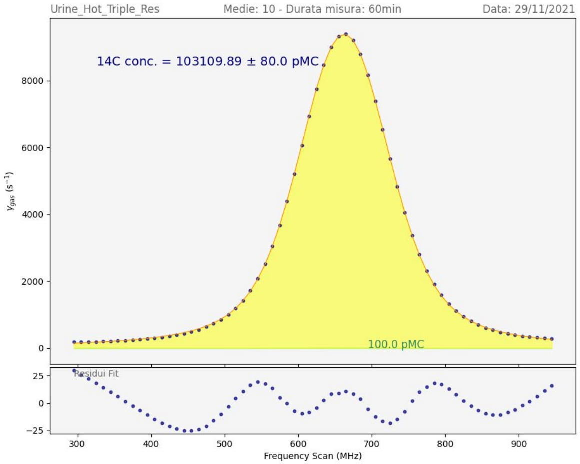
Fossil material: 0 pMC



Modern biogenic material: 100 pMC



Enriched human urine: ~10^5 pMC



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C14-SCAR: the world first radiocarbon spectrometer

- ✔ Compact and transportable Equipment
  $1 m^2$ footprint; 350kg weight
- ✔ Low power consumption (< 1kW)
- ✔ Maintenance-free operation
- ✔ The best sensitivity (<1 pMC)
- ✔ Unprecedented dynamic range
  from fossil to highly enriched samples
- ✔ Fast measurements
  10 minutes, 30 minute with sample preparation
- ✔ Works with any solid or liquid material

Sample preparation and measurement

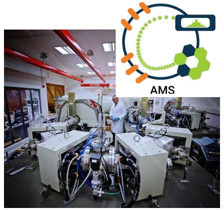
Sampling → Focusing → Measuring

Elemental Analyzer
By NCT / Elementar

CO_2 gas

Solids	Liquids	Gases
Plastics Wood Fabrics	Fuels Ethanol ...	Pure CO_2 Air Smokes

The competition: C14-SCAR provides the best precision with a fraction of cost and size



Accelerator Mass Spectroscopy (AMS) detects isotope ratio of ^{12}C, ^{13}C, ^{14}C ions. The use has increased, but its **economic and energy costs** make only ~20 instruments available in Europe.

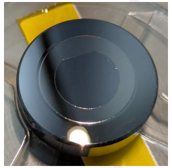
Liquid Scintillation Counting (LSC) uses β-decay counting, but with **insufficient precision** for monitoring applications, thus requiring large sample amounts, high isotope doses and difficult measure automation.

SCAR detects absorbed IR photons. It is demonstrated and sold for ^{14}C quantification for many applications. Qualification for spread use require **less sample needs, better modularity and automation.**

	14C SCAR	Ionplus AMS	HIDEX LSC
Size	✔	✘	✔
Weight	✔ KG	✘ KG KG KG KG KG	✔ KG
Minimum sample needs	✔	✔	✘
Precision measurement	✔ **HIGH**	✔ HIGH	✘ LOW
Dynamic range	✔ **VERY HIGH**	✘ LOW	✔ HIGH
Cost (€)	✔ **< 600 k**	✘ 1.5 – 5 M	✔ 150 k
Sample handling and preparation	✔ **Fully automatic**	✔ automatic	✘ manual

New developments: compact version

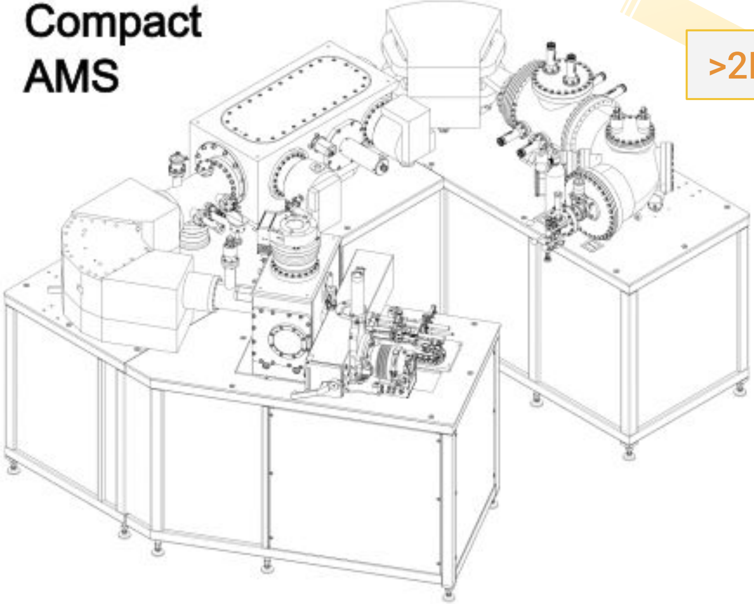
Better mirrors



Shorter optical cavity

More compact
Cheaper
Higher performance

Compact AMS



>2M€

600k€

<500k€

C14-SCAR

Gen1 (2021-2025)

14C SCAR

Gen2 (from 2025)

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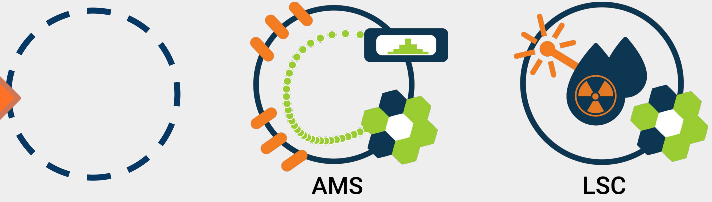
Method Accreditation - 1/3

Table 1 — Advantages and disadvantages of the methods

Method	Additional requests	ASD	RSD	Duration needed for measurement	Typical carbon mass needed	Equipment costs
Method A (LSC)	- Normal laboratory	5 pMC $\propto \sqrt{F}$	10 % $\propto 1/\sqrt{F}$	2 h to 24 h	> 1g	Low
Method B (AMS)	- Large installation - Graphite conversion device [a]	0,3 pMC $\propto \sqrt{F}$	0,3 % $\propto 1/\sqrt{F}$	10 min to 30 min	< 1 mg	High
Method C (SCAR)	- Normal laboratory - Gas purification device	1 pMC constant	1 % $\propto 1/F$	10 min to 6 h	1 mg to 10 mg	Intermediate

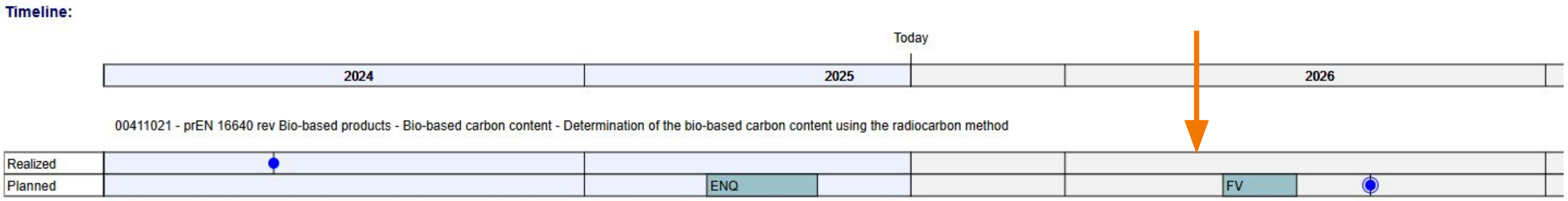


UNI EN 16640

Bio-based products - Bio-based carbon content

*Determination of the bio-based carbon content using the **radiocarbon** method*

- ✔ Gives a **legal validity** to the SCAR method
- ✔ Enables **normative adoption**
- ✔ Makes SCAR a **reference method** for calibrating other techniques



Method Accreditation - 2/3

The results of the AMS-SCAR blind intercomparison measurements over the 58 sets of samples are reported in the table below.

Campaign	Samples	Document	SCAR result (pMC)	AMS result (pMC)	Absolute Deviation (pMC)	Relative Deviation (%)	RMS error (pMC)
A 2019	SES1	RISE preliminary test	48	47	1	2,1%	2,65
	SES4		37	38	-1	-2,7%	
	9F026397 (plastic)		100	95	5	5,1%	
	9F020347-1 (plastic)		28	30	-2	-6,9%	
	9F020347-2 (plastic)		1	3	-2	-100,0%	
B 2021	BP1	RISE acceptance test & Report	48,74	49,2	-0,46	-0,9%	0,33
	BP2		89,5	89,4	0,1	0,1%	
C* 2021	Avionic Fuel Blend_1	Published paper: Biogenic Fraction Determination in Fuel Blends by Laser-Based 14CO2 Detection	5,6	4,74	0,86	16,6%	0,85
	Avionic Fuel Blend_2		74,6	76,04	-1,44	-1,9%	
	Upgraded Pyrolysis Bio-oil_1		37,8	38	-0,2	-0,5%	
	Upgraded Pyrolysis Bio-oil_2		46,8	47	-0,2	-0,4%	
D 2022	EVA "vegan" sole	Published paper: Material Circularity: A Novel Method for Biobased Carbon Quantification of Leather, Artificial Leather, and Trendy Alternatives	0,2	0,4	-0,2	-66,7%	1,45
	Desserto "Cactus Leather"		24,1	23,58	0,52	2,2%	
	Coated patent leather		47,1	48,09	-0,99	-2,1%	
	Mix synthethic-natural fabric		61	62,3	-1,3	-2,1%	
	Fully syntan tanned leather		65,6	67,62	-2,02	-3,0%	
	Soft milled leather "Rave"		92,6	90,12	2,48	2,7%	
	Vachetta leather "Toiano"		94,8	96,01	-1,21	-1,3%	
E 2022	Diesel	Internal document	3,8	4,5	-0,7	-16,9%	0,53
	Gasoline 1		2,8	2,6	0,2	7,4%	
	Gasoline 2		0	0,7	-0,7	-200,0%	
	Jet A		1,2	1,5	-0,3	-22,2%	
F 2023	SampleA	Support Letter	69,1	70,08	-0,98	-1,4%	1,39
	SampleB		80	82,22	-2,22	-2,7%	
	SampleC		75,5	78,05	-2,55	-3,3%	
G 2023	s_861	Internal report	0,76	0,05	0,71	175,3%	0,61
	s_923		26,04	25,33	0,71	2,8%	
	s_855		57,62	56,8	0,82	1,4%	
	s_1088		80,34	79,9	0,44	0,5%	
	s_1049		101,53	100,92	0,61	0,6%	
	s_932		115,52	115,5	0,02	0,0%	
H 2023	PP 1	Published paper: A laser-based saturated-absorption cavity ring-down technology for precise biobased content analysis of plastic samples	1,08	0,49	0,59	75,2%	0,65
	PP 2		0,3	0,75	-0,45	-85,7%	
	PP 3		0,56	0,73	-0,17	-26,4%	
	PLA drinking straw		70,42	70,22	0,2	0,3%	
	Plastic 2 kg bag		29,33	31,31	-1,98	-6,5%	
	Compostable green plastic bag		23,73	23,91	-0,18	-0,8%	
	Compostable black plastic bag		28,95	29,39	-0,44	-1,5%	
	Compostable 10 kg plastic bag		27,39	28,21	-0,82	-2,9%	
	140 L plastic bag		27,14	26,67	0,47	1,7%	
	Recyclable plastic bag		0,23	0,79	-0,56	-109,8%	
	PCL plastic thread		0,17	0,28	-0,11	-48,9%	
	Degradable plastic bag		29,29	30,08	-0,79	-2,7%	
	(R)C-PLA plastic bag		95,99	96,4	-0,41	-0,4%	
	PLA plastic bag dog excrement		10,26	9,83	0,43	4,3%	
	Sugar cane plate		101,61	102,15	-0,54	-0,5%	
	PLA 2 dL plastic cup		100,63	101,49	-0,86	-0,9%	
	PLA 4 cL plastic cup		102,63	102,2	0,43	0,4%	
	C-PLA spoon		97,07	96,52	0,55	0,6%	
	50 mL plastic cup		0,78	0,1	0,68	154,5%	
	White plastic plate		0,29	0,17	0,12	52,2%	
	Plastic spoon 1		0,28	0,03	0,25	161,3%	
	Plastic spoon 2		0,56	0,13	0,43	124,6%	
	Rubbish bag		2,24	1,44	0,8	43,5%	
	1 L plastic bag		0,21	0,64	-0,43	-101,2%	
I 2024	Mater Bi - A3	Internal report	70,7	69,5	1,2	1,7%	1,37
	Plastic - A4		59,5	61,95	-2,45	-4,0%	
	Shopper plastic - B2		30,3	30,5	-0,2	-0,7%	
	Plastic - C2		37,35	37,6	-0,25	-0,7%	
J 2024	Horse bone from 1812	Internal report	96,55	96,98	-0,43	-0,4%	0,33
	Bone blank, no 14C		0,3	0,0	0,3	200,0%	
	SampleC		152,49	152,72	-0,23	-0,2%	

* The SCAR measurements performed in this test are not blind and are not included in Table G.4.

Total rms	1,01	pMC
Max Dev	2,48	pMC
Avg	-0,27	pMC

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Method Accreditation - 3/3

The results of performed assessment show a good consistency between method B (AMS) and method C (SCAR).

A low number of outliers (1) was observed, and the average discrepancy (with sign) is very close to 0 (-0,27 pMC), suggesting that no systematic bias is present between the two methods.

The **agreement** between the two methods of the more recent campaigns is settling on a level lower than 1 pMC, while the total RMS deviation over the full set of results is **1,01 pMC**.

AMS Round Robin

Table FG.2 — Performance data for 14C methods

Sample	n	l	o	x	s_R	CV_R
			%	% m/m	% m/m	%
1	10	8	20	10,2	1,8	17,7
2	10	9	10	14,4	1,5	10,6
3	10	9	10	96,7	0,8	0,9
4	10	9	10	94,0	1,4	1,5
5	10	9	10	97,3	2,3	2,3
6	4	3	25	96,0	1,7	1,8
7	10	10	0	98,0	1,0	1,1
8	10	9	10	95,0	1,4	1,5
9	11	10	9,1	12,2	1,2	10,1
10	10	9	10	73,2	2,0	2,7
11	10	9	10	94,1	1,8	1,9
12	11	11	0	99,3	0,8	0,8
	Meas # 116	Outl # 11		σ_{avg} Δ_{max}	1.54 2.30	

n is the number of laboratories

l is the number of outlier free individual analytical values

o is the percentage of outlying values

x is the overall means

s_R is the reproducibility standard deviation

CV_R is the coefficient of the variation of the reproducibility

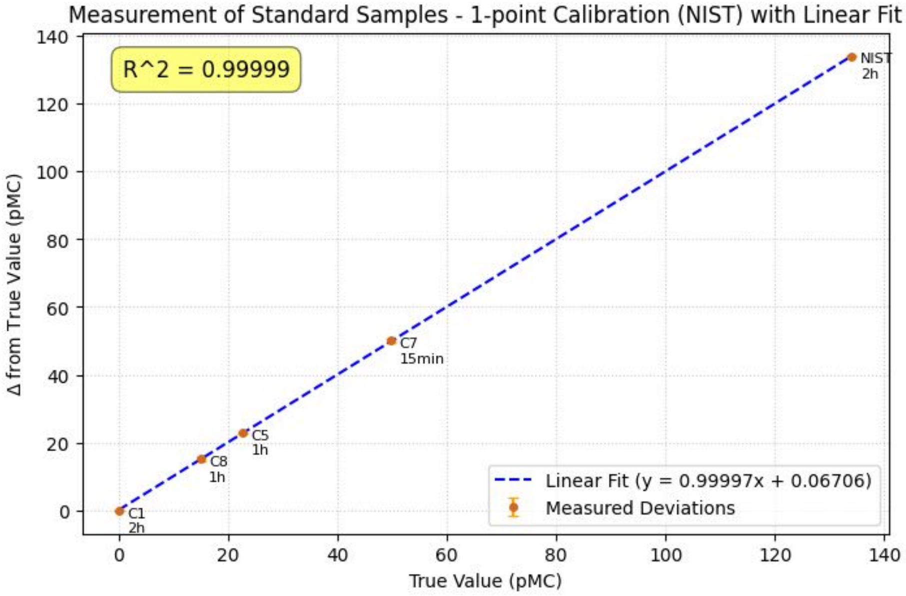
	EN 16640:2017 **Table G.2**	SCAR vs AMS **Table G.4**
# of measurements	116	58
# of outliers	11	1
# of individual instruments involved	>11	>7
Reproducibility σ_{avg} or RMSE	**1.54 pMC**	**1.01 pMC**
Reproducibility Δ_{max}	**2.30 pMC**	**2.48 pMC**

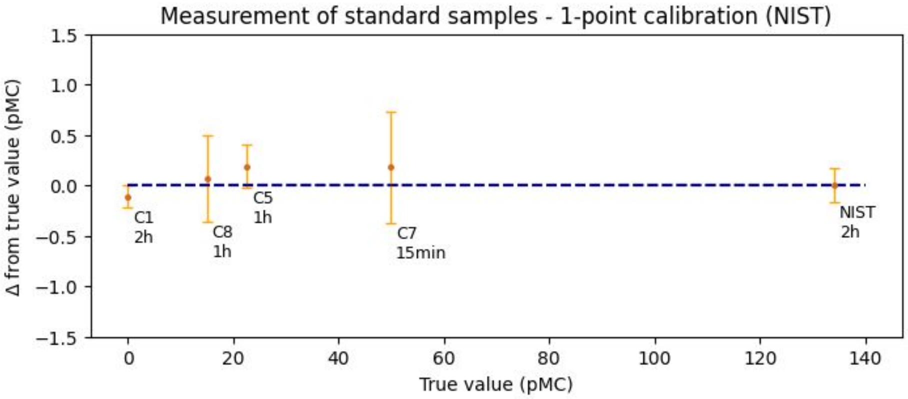
Comparison between the total average reproducibility standard deviation of Method B (1.54 pMC), as retrieved by averaging over the S_R column of table G.2 and the total average discrepancy between Method B and Method C (1.18 pMC).

Performances overview: accuracy

Measurements of Standard Samples
1-point calibration against NIST sample

Sample	Value (pMC)	Meas (pMC)	Error (pMC)	Abs Dev (pMC)
C1	0,00	-0,108	0,112	**-0,11**
C8	15,01	15,08	0,43	**0,07**
C5	22,69	22,87	0,21	**0,18**
C7	49,86	50,03	0,55	**0,17**
NIST	134,06	134,06	134,05	**0,00**
			RMS Dev	**0,14**





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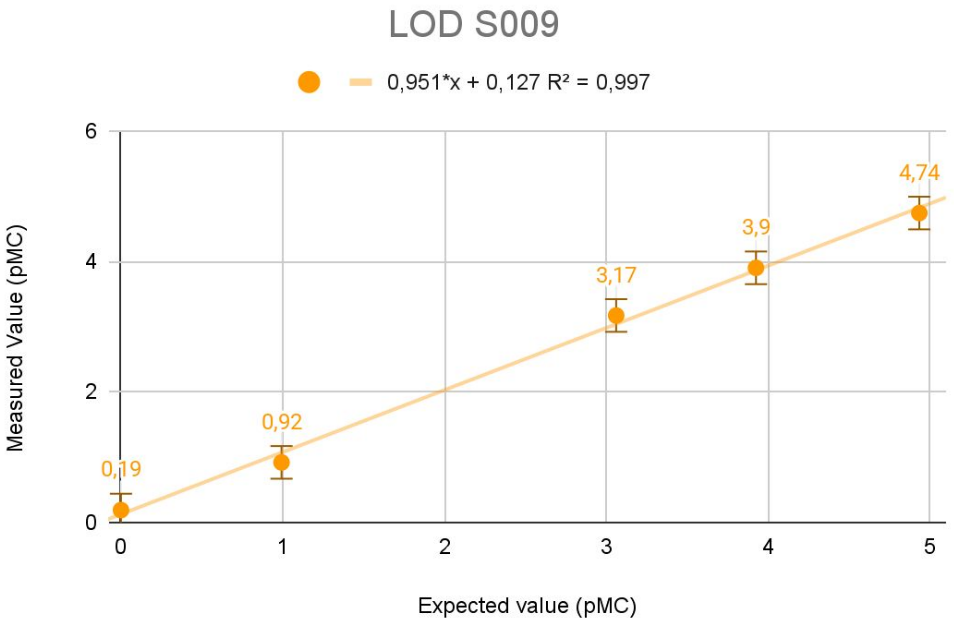
Performances overview: LOD

Expected Value (pMC)	Result (pMC)	Error (pMC)	Discrepancy (pMC)
0,00	0,19	0,34	0,19
0,99	0,92	0,28	-0,07
3,06	3,17	0,32	0,11
3,93	3,9	0,13	-0,03
4,94	4,74	0,22	-0,20
		AVG	**0,001**
		SD	**0,152**



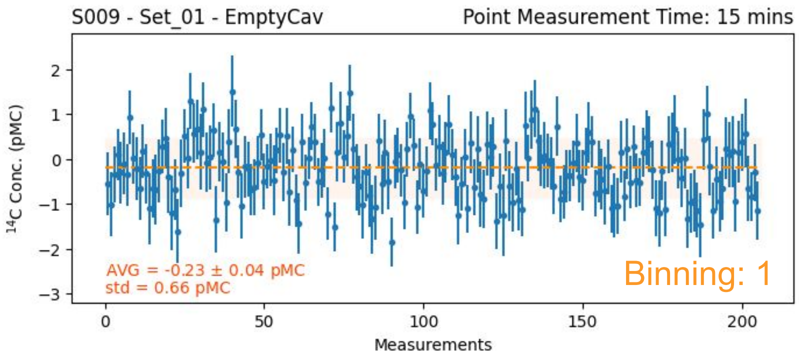
Linear Regression Parameters	
Slope (m)	0,951 ± 0,032
Intercept (q)	0,127 ± 0,102
LOD (3 errq / m)	0,32 pMC

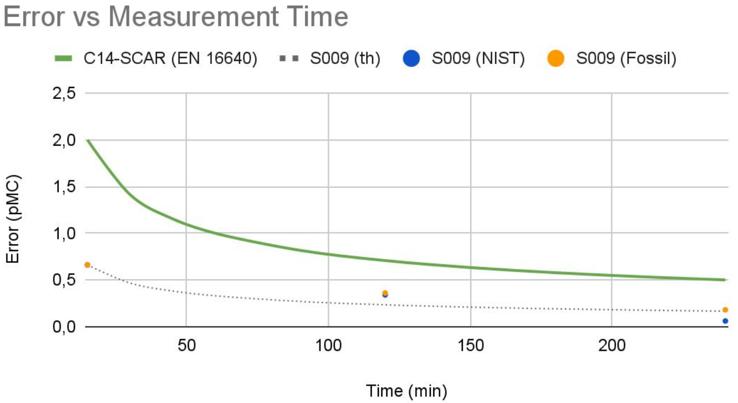
Measurement time: 2h

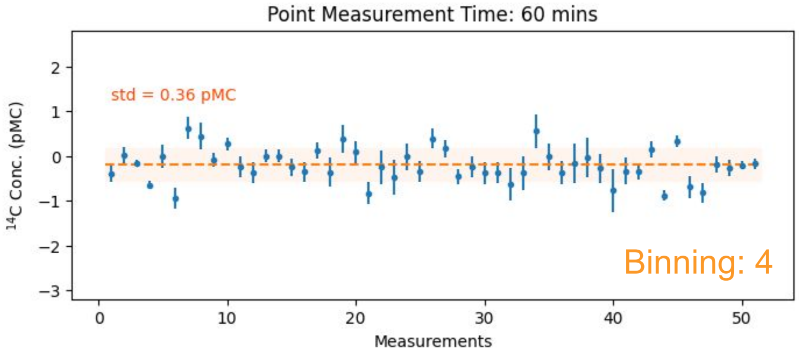
LOD = 0.32 pMC

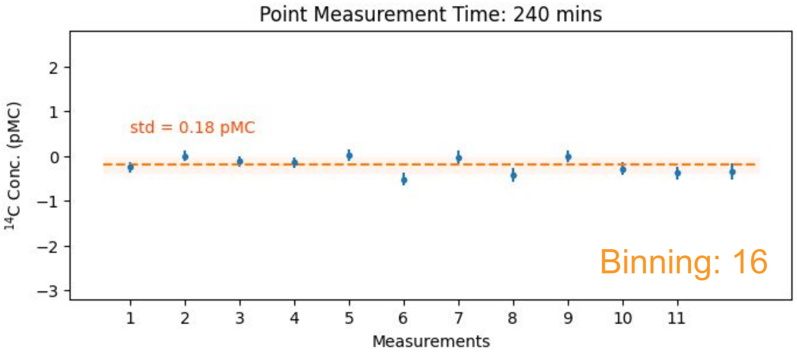
Performances overview: stability and precision

51h-long (205 measurements) on empty cavity. Precision scales with the measurement time.









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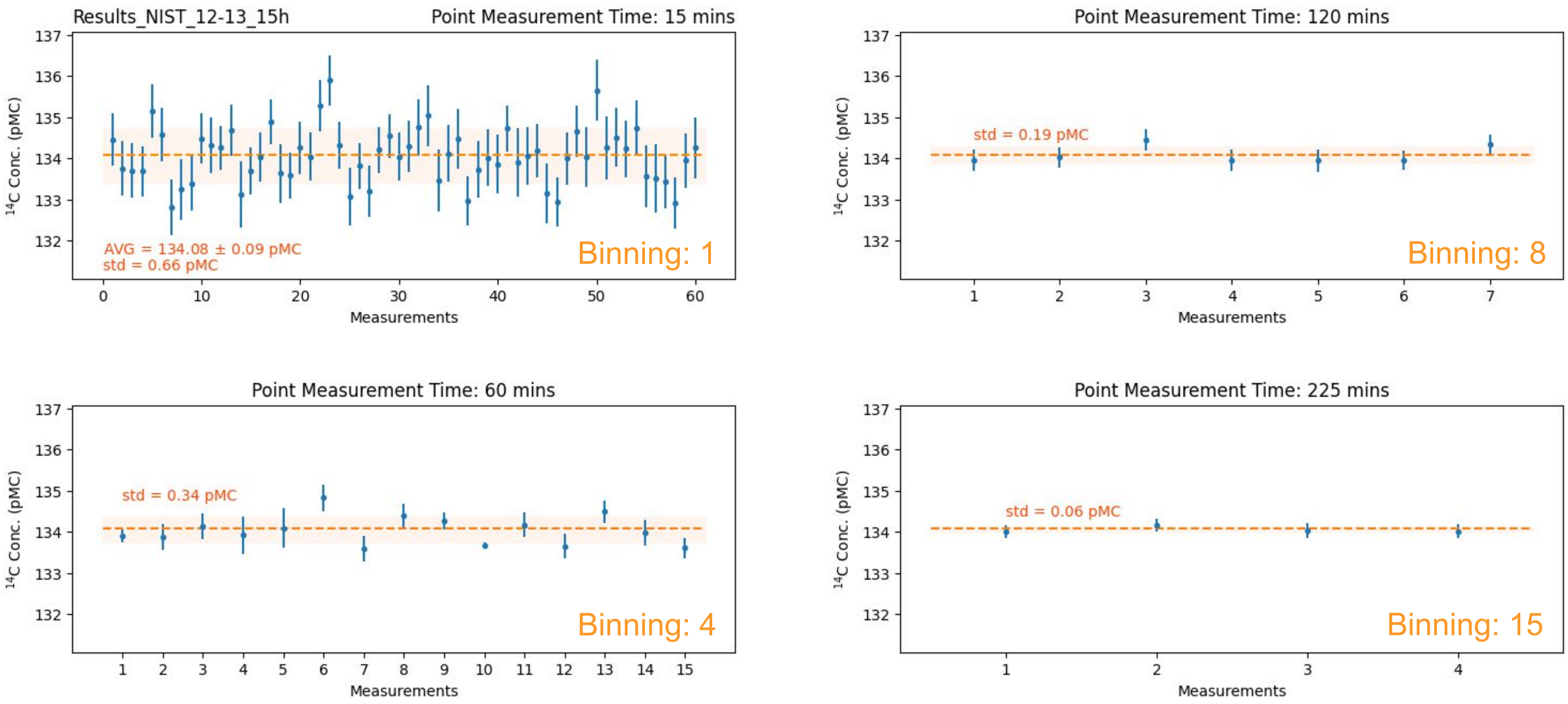
Performances overview: stability and precision

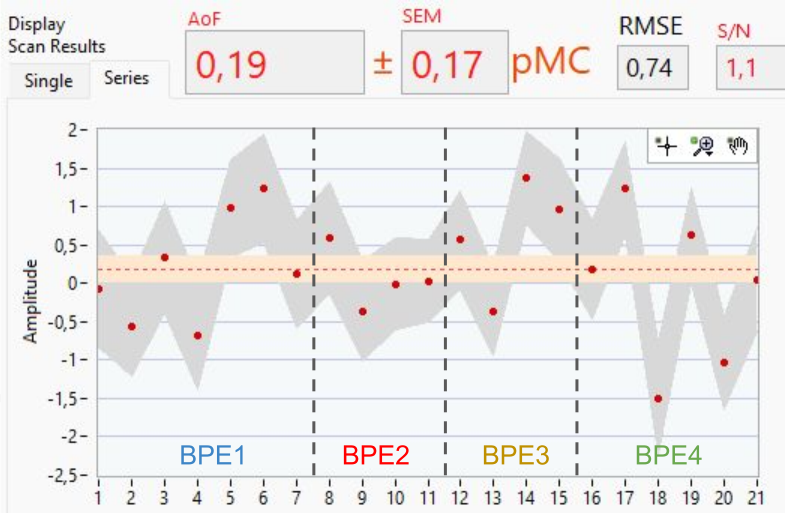
SCAR009

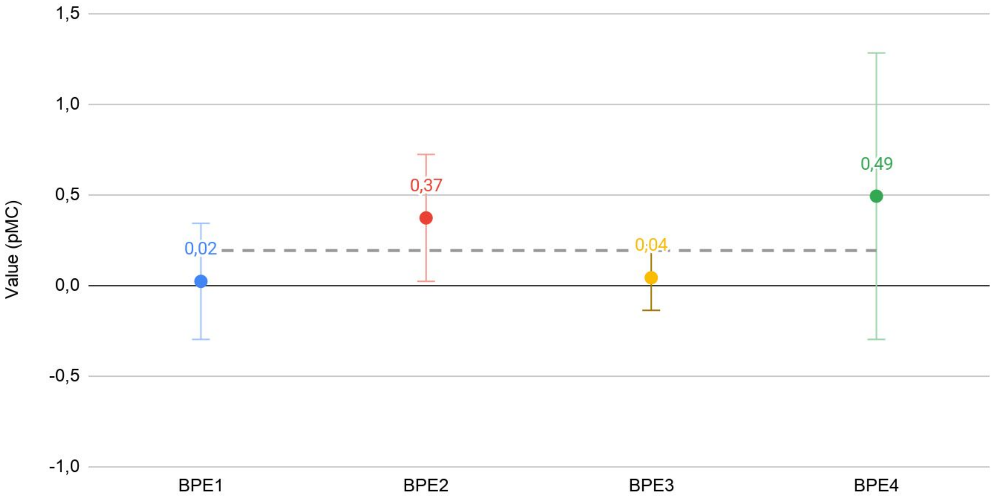
15h-long (60 measurements) on NIST standard. Precision scales with the measurement time.



Performances overview: overall repeatability

Repeated measurement cycle (preparation, burning and measuring) on a Fossil sample





The repeatability of the full process gives an overall standard deviation similar to that obtained within a series of repeated measurements on the same sample (see previous slides).

14C SCAR

Use cases

C14-SCAR instruments delivered in 3 years

RI. SE

- Biogenic fraction determination in materials
- ASTM D6866 certified C14-SCAR lab

European Commission

- Nuclear safety analyses
- Installing C14-SCAR in an hot-lab (high radioactivity)

Empa
Materials Science and Technology

- Atmospheric radiocarbon dioxide studies
- Automatic continuous monitoring system

Italian National Research Council

- New developments of SCAR techinque
- Sub-ppq sensitivity by using new super-mirrors

ARS TINCTORIA
CTC

- Biobased content in fabrics/plastics/leather
- Measurement service for fashion brands

Italian National Research Council
E-RIHS.it
EUROPEAN RESEARCH INFRASTRUCTURE FOR HERITAGE SCIENCE

- Dating applications

Italian National Research Council
ICOS
INTEGRATED CARBON OBSERVATION SYSTEM
Riuni

- Atmospheric radiocarbon dioxide studies
- Part of the international ICOS network

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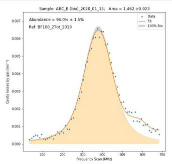
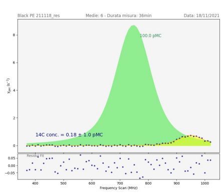
14C SCAR
Collaborations and Measurement services

RISE Research Institutes of Sweden



Biodiesel/Diesel Mixtures

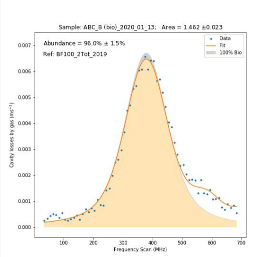
Plastics



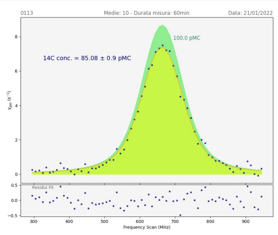
Italian Ministry for Environment
Consiglio Nazionale delle Ricerche

Bio-fuels for aviation

MINISTERO DELL'AMBIENTE
E DELLA TUTELA DEL TERRITORIO E DEL MARE

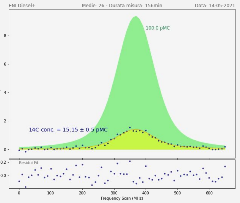


NESTE



Chevron eni

Analysis of commercial bio-fuels

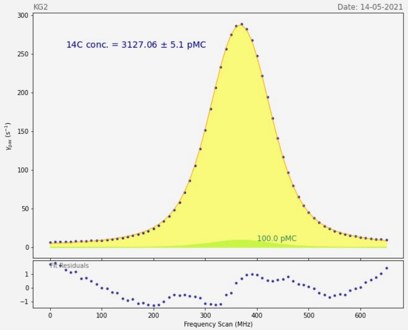


European Commission
DG Joint Research Centre – JRC
Directorate G
Nuclear Safety & Security

European Commission

Materials and air from nuclear power plant

ENEA

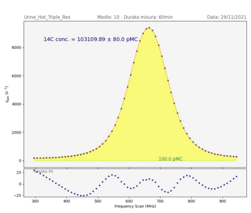


GSK

TNO

MERCK

SHIMADZU
Excellence in Science



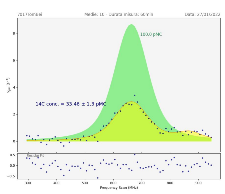
Determination of biogenic carbon content in materials

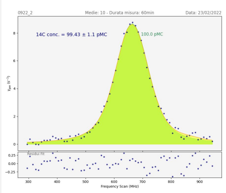
ARS TINCTORIA

CTC

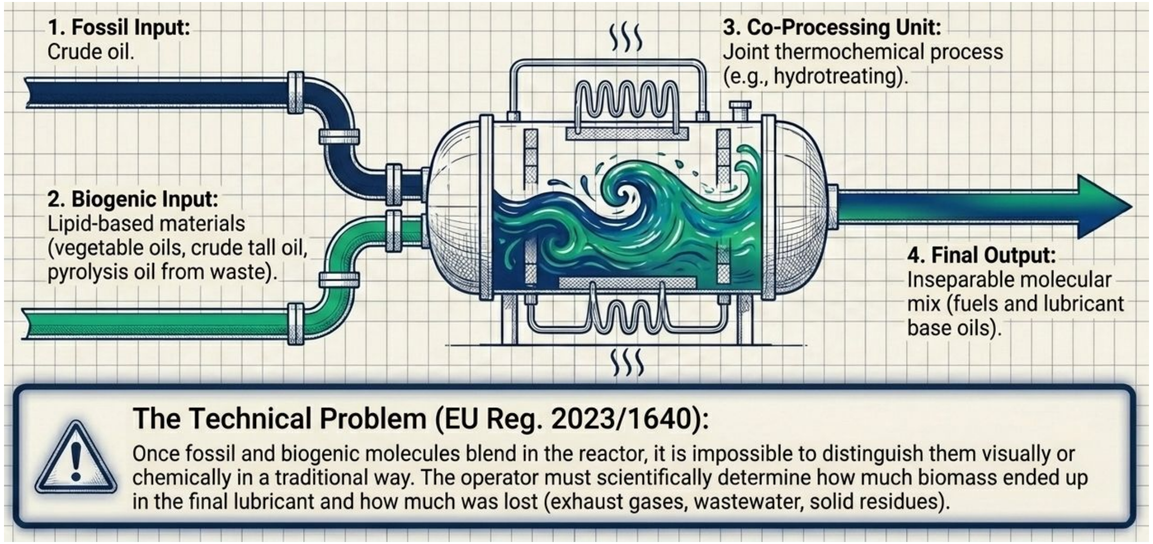
atomki

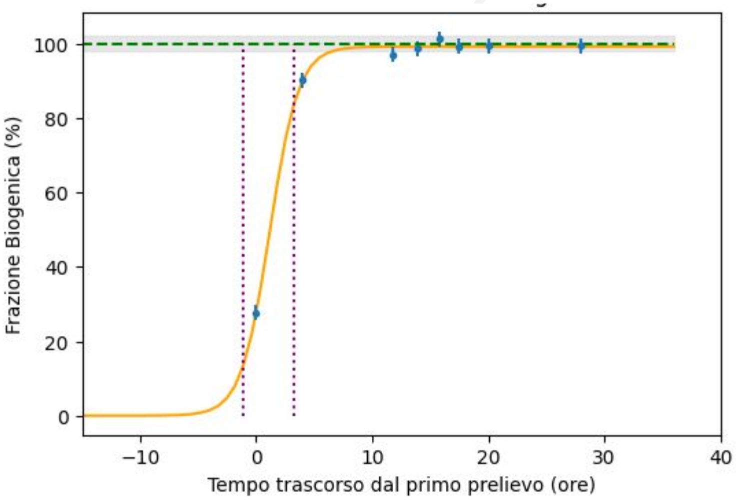
NOVAMONT
A Versalis Company

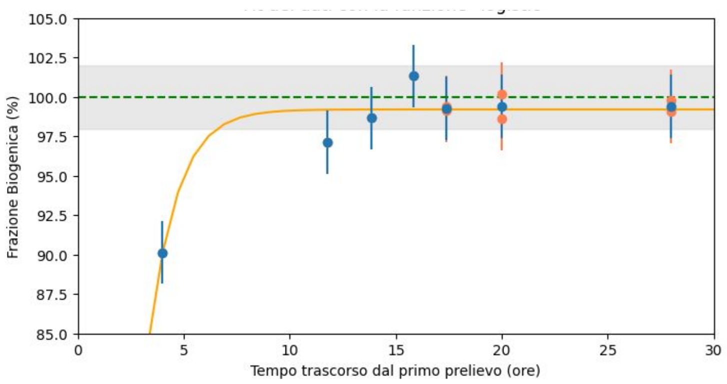




Real-time monitoring of a refinery







C14-SCAR is the only technology that can enable these types of applications, offering several unique advantages:

- Rapid results: Turnover in less than one hour.
- Versatile deployment: Suitable for on-field or in-situ use.
- Low maintenance: Minimal upkeep required.
- Cost-effective: Low deployment and operational costs.

SENSE

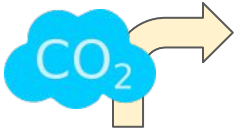
Atmospheric ^{14}C monitoring by SCAR

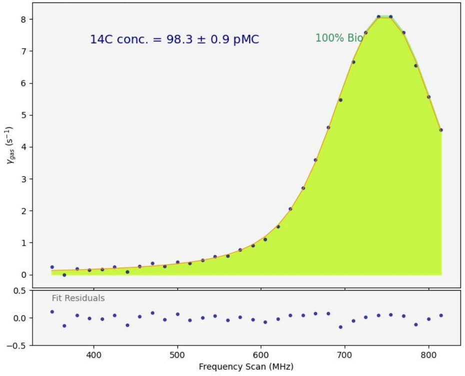
Atmospheric CO_2 can be directly sampled from air and analyzed by C14-SCAR

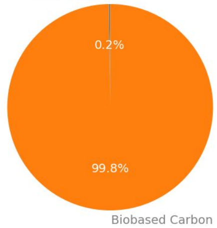
CO_2 sampler & Purifier

Portable CO_2 sampler

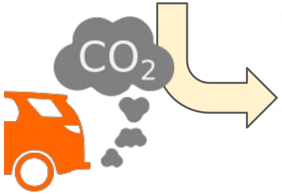
Car exhaust



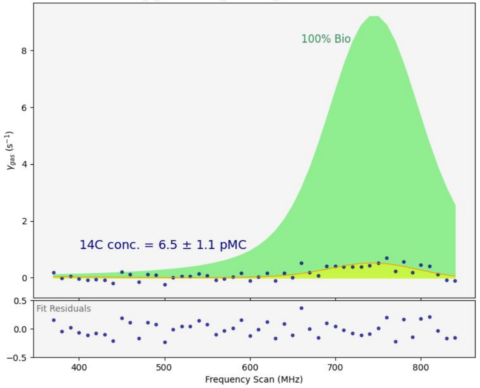


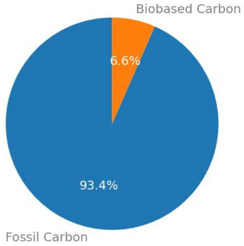


Biobased Carbon Content: 100%



Car exhaust

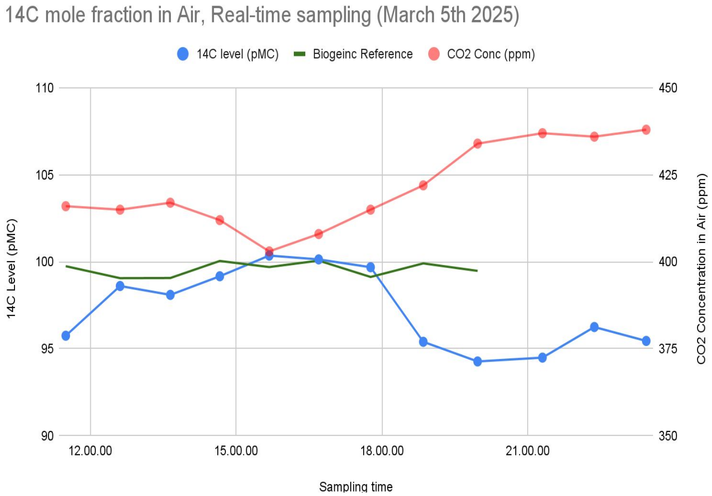


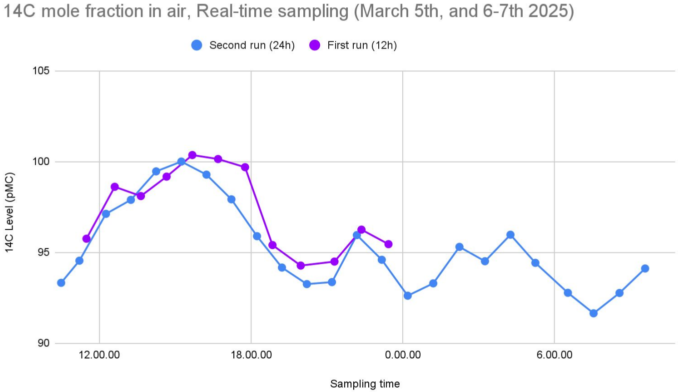


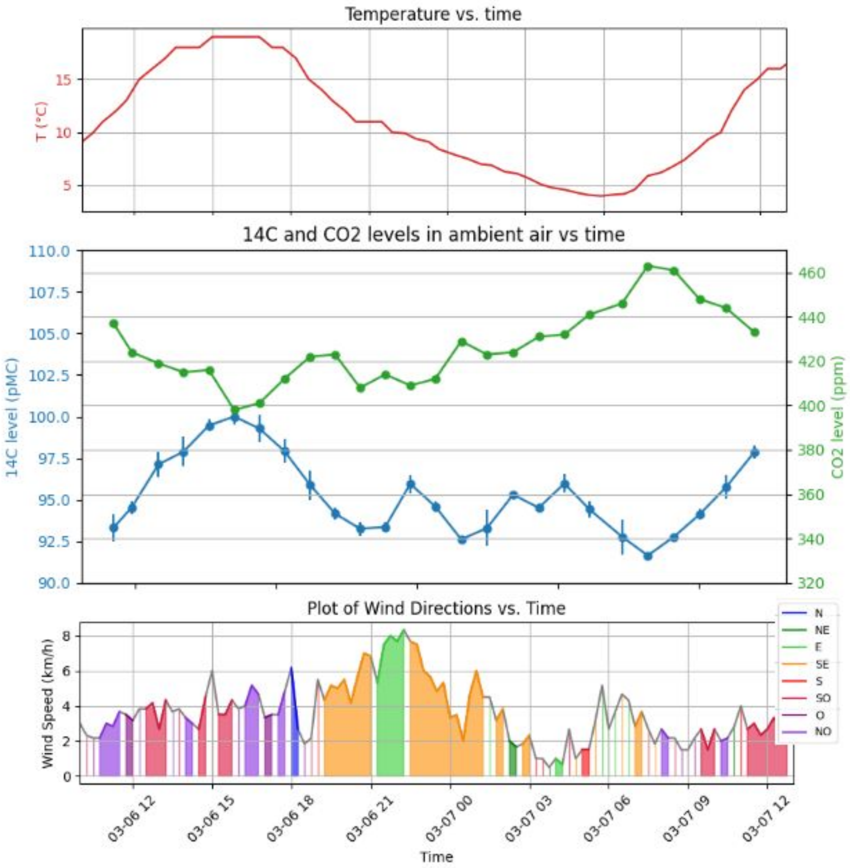
Biobased Carbon Content: 7%

The whole process is automatic, with no cryogenics involved

Quasi-continous atmospheric montoring







14C SCAR

Thank you!