Carbon footprint assessment for IRAP
Final report

Pierrick MARTIN, Jürgen KNÖDLSEDER
pour la Commission Environnement-Transition de l'IRAP

JST - 08 Février 2022

Contents

- ~~Motivation for the work: global warming~~
- Bilan Carbone© methodology: principles and practice
- Scope of the assessment
- Results
- Specific case of astronomical research infrastructures
- Avenues for reduction

Note:
GHG = greenhouse gases
CO_2, CH_4, N_2O,…

Carbon accounting

- Key principles
  - Decision-making tool in view of low-carbon transition strategy
  - Identify emissions an activity depends on/generates while running
  - Determine maximum leverage for action (on input and output flows)

Can I still perform my activity according to current standards if a certain source of emissions is removed ?

In practice:

GHG amount = activity data (AD) x emission factor (EF)

Example: 120 kg CO_2eq = 2000 kWh x 0.06 kg CO_2eq/kWh

Main difficulties: AD not always accessible or accurate
major uncertainties on some EF

Note: CO_2eq includes gases other than CO_2: CH_4, N_2O,…

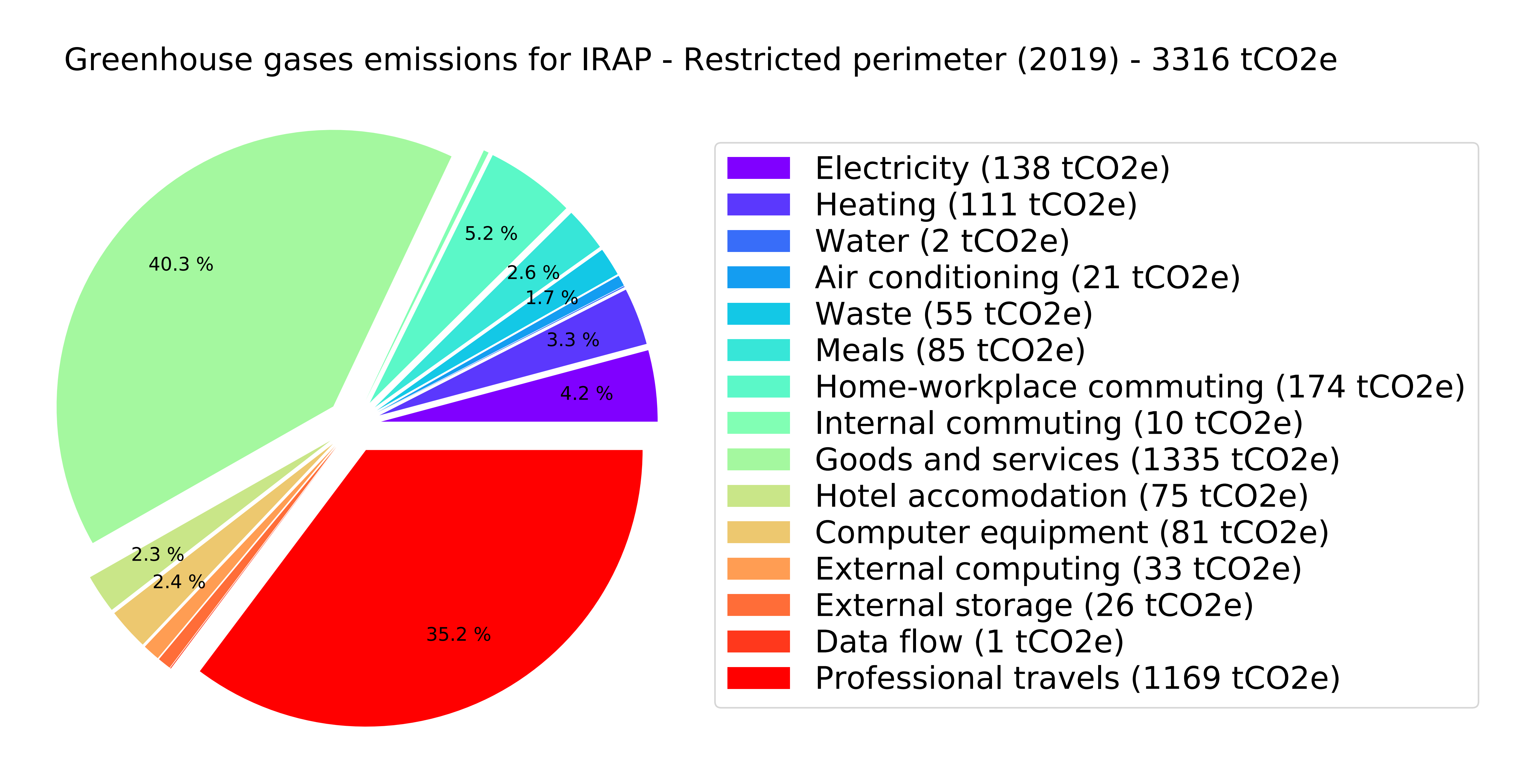
Scope

- Reference year: activity period concerned
  - 2019 (pre-covid)

- Organisation: facilities, staff, and activities concerned
  - Sites: Belin, Roche, Tarbes
  - People: 116 C/EC - 78 ITA/CDD - 69 PhD/Postdocs = 263 pers.
  - Activities: all except most of teaching and some support services

- Operations: GHG-emitting operations concerned
  - Direct emissions (ex: own vehicles) - Scope 1
  - Indirect emissions from energy (ex: electricity) - Scope 2
  - Other indirect emissions (ex: travels, purchases) - Scope 3

Results (restricted perimeter)

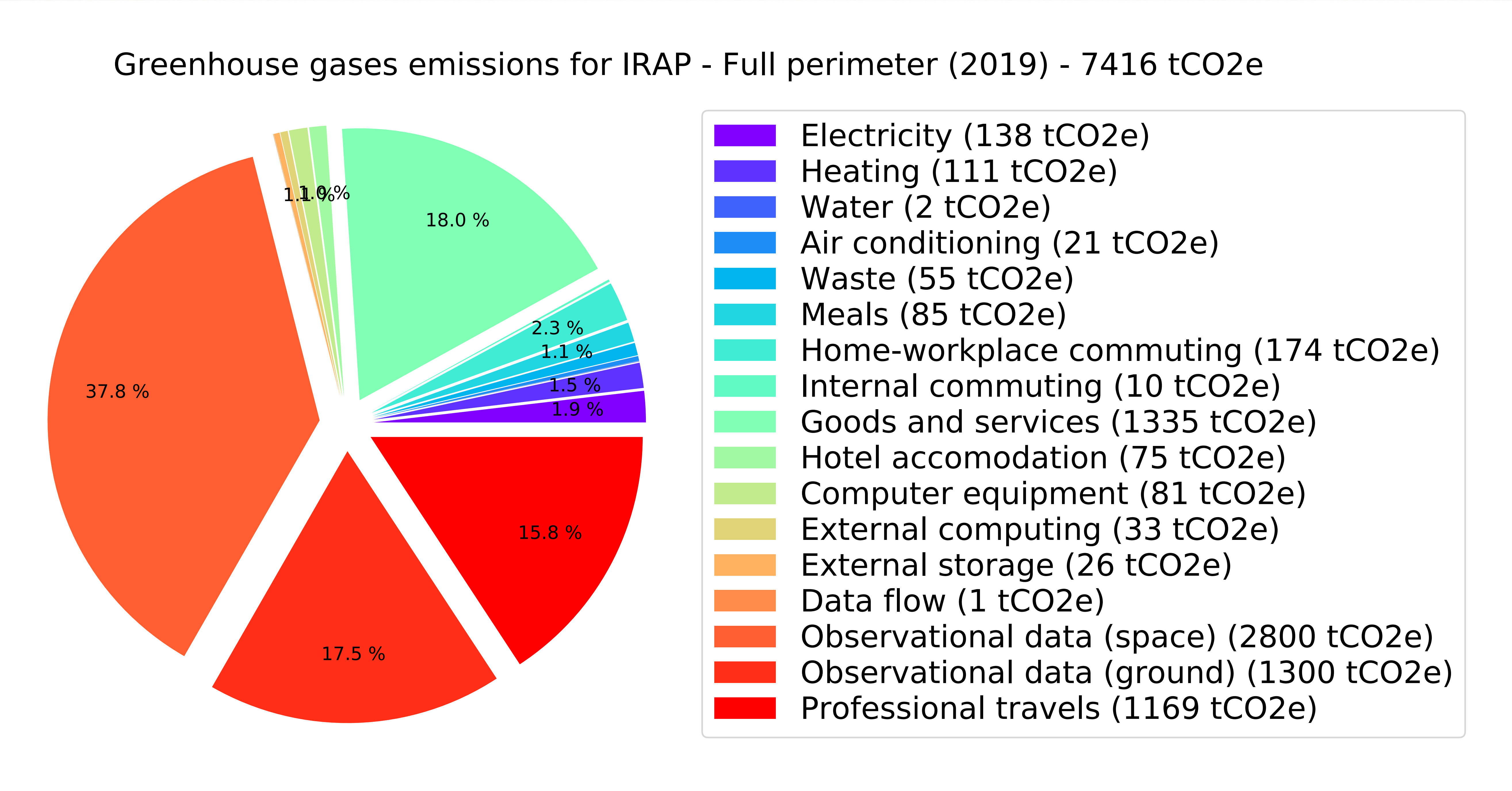


Local infrastructure subdominant (~800 tCO2e)

Heating/Electricity emissions pretty low because low-carbon sources (wood,nuclear)

Typical uncertainties +/- 20-50% - Formally a lower limit

Results (full perimeter)



The use of external research infrastructures dominates (see next part)

Astronomical research infrastructures

- **Astronomical Research Infrastructures**
  - Space telescopes
  - Space probes (plasma, planetary)
  - Ground-based observatories

- **Why should astronomers consider their footprint?**
  - Without astronomical research infrastructures astronomy would not be possible (astronomers depend on them)
  - Furthermore astronomers have some responsibility
    - Astronomers invent Research Infrastructures and contribute to building/operating them (share in responsibility)
    - Without astronomers there wouldn’t be any astronomical research infrastructures

Emission factors

Activity	Emission factor
Space missions (based on payload wet mass)	50 t CO_2e / kg
Space missions (based on mission cost)	140 t CO_2e / M€
Construction of ground-based observatories	240 t CO_2e / M€
Operations of ground-based observatories	250 t CO_2e / M€

Selected other activities for comparison

Activity	Emission factor
Insurance, banking and advisory services,	110 t CO_2e / M€
Architecture and engineering, building maintenance	170 t CO_2e / M€
Installation and repair of machines and equipment	390 t CO_2e / M€
Metal products (aluminium, cupper, steel, ...)	1700 t CO_2e / M€
Mineral products (concrete, glass, ...)	1800 t CO_2e / M€

Our emission factors are on the low side of other sector-based values.
Will make decarbonisation challenging.

Their carbon footprint

We computed the lifecycle and annual carbon footprint of 85 astronomical research infrastructures used by IRAP researchers for refereed publications in 2019

Category	Lifecycle footprint ($Mt\ CO_2e$)	Annual footprint ($kt\ CO_2e$ / yr)
Space missions	4.8 ± 0.6	338 ± 49
Ground-based	3.0 ± 0.8	194 ± 64
Total	7.8 ± 1.4	532 ± 106

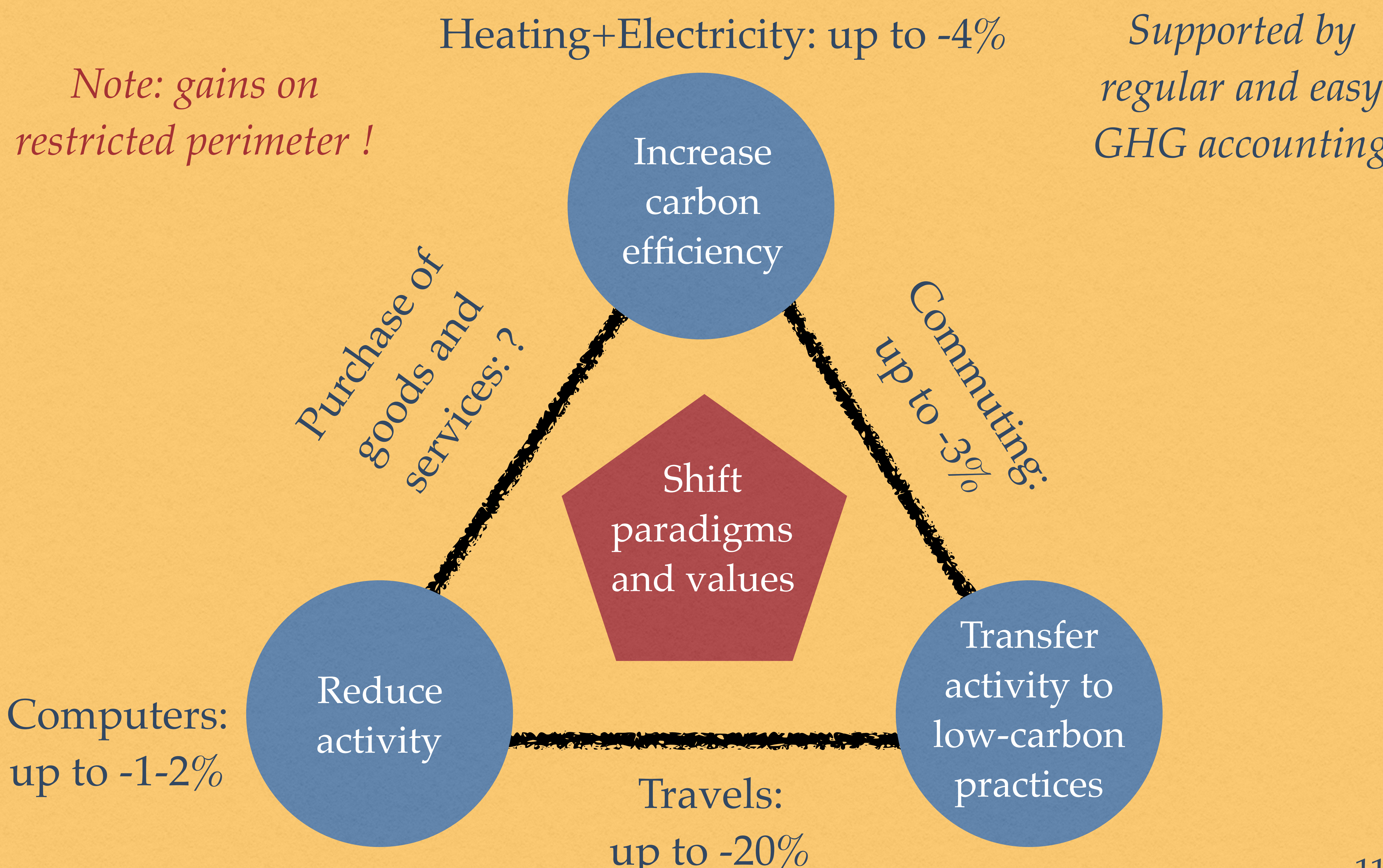
Uncertainty in carbon footprint of individual facility assumed to be 80%. For total carbon footprints, uncertainties are summed in quadrature.

Footprint attribution to IRAP

We attributed the footprint of each facility based on the fraction of IRAP authors that co-signed papers using a given facility in 2019 (fraction typically ~ 1%). Summing over the attributions gives the IRAP share of the carbon footprint.

Category	IRAP carbon footprint (t CO_2e)
Space missions	2 663 ± 388
Ground-based	1 289 ± 490
Total	3 953 ± 689
Per IRAP staff (263)	15.0 ± 2.6

Avenues for reduction



Key messages

- Carbon footprint assessment for IRAP in 2019 is now over
  - Extended scope including almost all facets of research activity
  - Final paper nearly ready (and one published on infrastructures)
  - Will be made available to all of you

- Operating IRAP requires 7400 tCO_2e/yr or 28 tCO_2e/yr/staff member
  - 4100 tCO_2e from use of external research infrastructures
  - 1300 tCO_2e from purchase of goods and services (for instrument development)
  - 1200 tCO_2e from professional travels (mostly air)
  - 800 tCO_2e only from local infrastructure

- Avenues for reduction: we need to use all levers !
  - Local/shorter-term perimeter: travels, commuting, computers
  - Intermediate: purchases/low-carbon technologies
  - Community-scale/longer-term: rethinking infrastructures

Now entering reduction phase.
Please contribute to design/implementation !

Acknowledgments

- Many thanks to
  - Philippe Louarn, Christelle Feugeade, Josette Garcia
  - Jean-Louis Lefort, Marjorie Cloup
  - Teddy Baï, Cédric Hillembrand
  - Pauline Bénard
  - Jean-François Botte, Sélim Benguesmia
  - Marie-Pierre Arberet, Stéphanie Baylac, Sylvie Cieutat
  - Danièle Millet
  - DR14 for the IFC training
  - Our OMP colleagues

Backup slides

Purchase of goods and services

ID	Category	Expense (k€)	Emission (t CO_{2e})	Share (%)
E	Consulting/Insurance/Human Resources	493	122	9.17
I	Computing/Telecommunications	668	117	8.77
O	Optical	518	174	13.01
T	Electronics	673	262	19.64
R	Mechanics/Automation	354	144	10.78
C	Communication/Documentation	159	44	3.30
P	Nuclear/Particle Physics	144	134	10.02
A	General supplies	139	59	4.43
F	Freight/Transport	43	28	2.16
V	Vacuum	82	55	4.10
B	Buildings/Infrastructure	128	53	3.96
G	Cryogenics/Laboratory gases	28	28	2.10
N	Chemistry/Biology	47	54	4.05

Table 5: Distribution of the main sources of GHG emissions in the purchase of goods and services, listing only those with an individual share $> 2\%$ (which together cumulate to more than 95% of the total). The first column corresponds to the identifier in the French NACRES nomenclature.

Avenue for local reductions

Scenario	Emissions	Gain
Professional travels (2019: 1169 t CO_{2e} or 35% total)		
1 - Train in FR	952	-19% (total: -7%)
2 - Plane 2 non-EU	977	-16% (total: -6%)
3 - Train in FR, Plane 4 EU+2 non-EU	719	-38% (total: -14%)
4 - Train in FR, Plane 2 EU+1 non-EU	508	-57% (total: -20%)
Commuting (2019: 185 t CO_{2e} or 6% total)		
1 - <2.5km bike/foot & -20% car	155	-16% (total: -1%)
2 - <5km bike/foot & -40% car	125	-32% (total: -2%)
3 - like 2 with 50% electric/hybrid cars	103	-44% (total: -3%)
4 - 3 days remote working	152	-18% (total: -1%)
Meals (2019: 85 t CO_{2e} or 3% total)		
1 - 50% classical meals $\mapsto$ flexitarian	65	-24% (total: -1%)
2 - 50% flexitarian+50% vegetarian	37	-56% (total: -1%)
3 - 100% vegetarian	22	-63% (total: -2%)
Computer equipment (2019: 81 t CO_{2e} or 2% total)		
1 - 4-year lifetime for computers	59	-27% (total: -1%)
2 - 6-year lifetime for computers	50	-38% (total: -1%)
Heating and electricity (2019: 111+138 t CO_{2e} or 3+4% total)		
1 - Heating -49% by 2030	57	-49% (total: -2%)
2 - Electricity -49% by 2030	70	-49% (total: -2%)

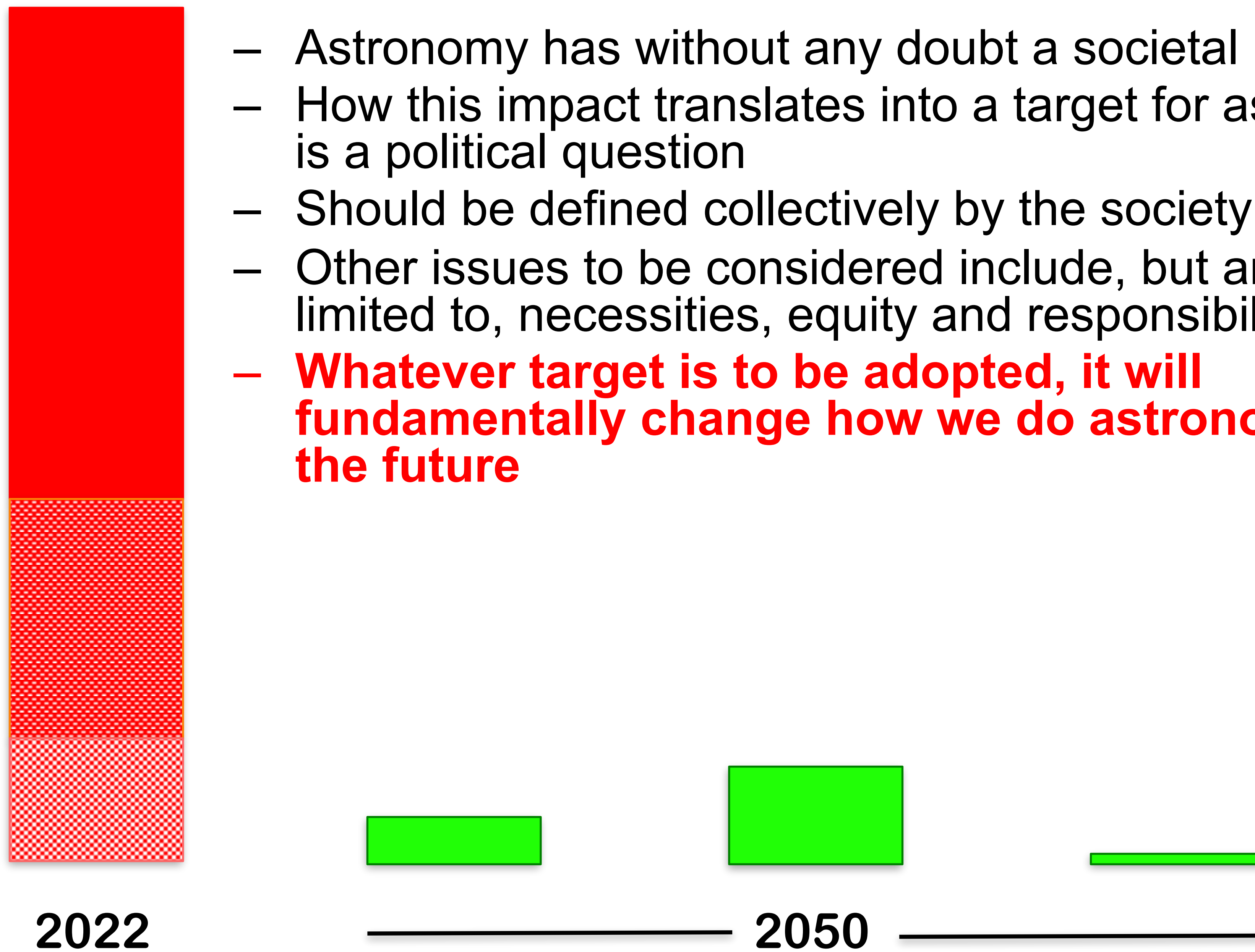
Table 7: Benefits from various reduction scenarios. The gain column gives first the relative gain, the decrease for the source of emission under consideration, and second the total gain, the decrease of the total footprint without the impact of using external research infrastructures use (i.e. 3316 t CO_{2e}).

Professional travels

Add plots from Philippe once reformatted

What’s our target?

- Astronomy has without any doubt a societal impact
- How this impact translates into a target for astronomy is a political question
- Should be defined collectively by the society
- Other issues to be considered include, but are not limited to, necessities, equity and responsibility
- **Whatever target is to be adopted, it will fundamentally change how we do astronomy in the future**



Hickel, J., Lancet Planet Health, 4, 399 (2020) →

Generic Method

Boundaries
Infrastructures used by IRAP in 2019; cover construction, launch and operations

Emission factors
e.g. tonnes of CO_2e per M€ spent

Carbon footprint $= \sum_{i=1}^{N} A_i \times EF_i$

Activity data
e.g. mission cost, payload weight, operation costs

Method of calculation

- **Space missions**

$$\text{Carbon footprint}_{\mathrm{c/m}} = A_{\mathrm{c/m}} \times EF_{\mathrm{c/m}}$$

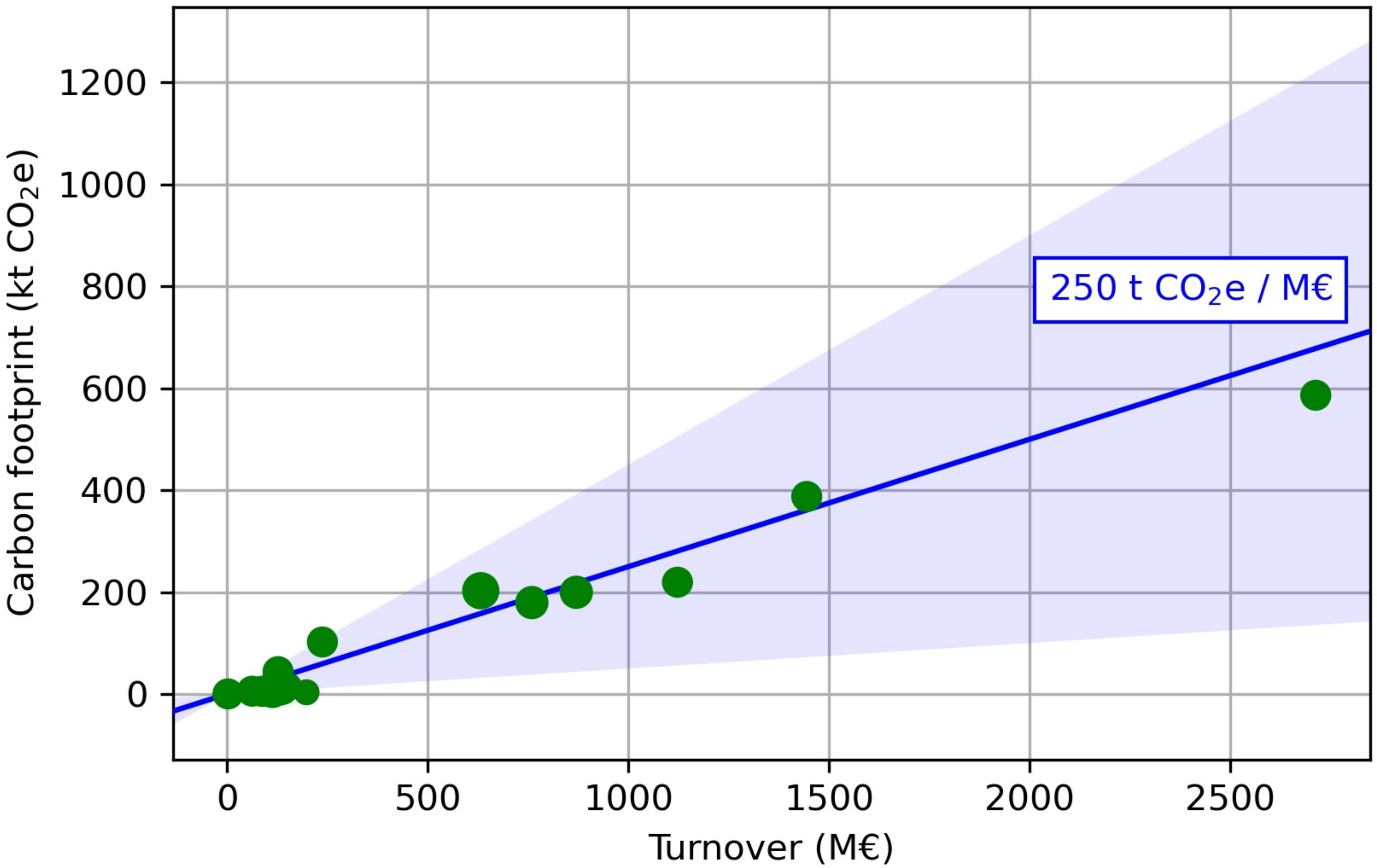
  - Full mission cost or payload launch mass as activity data
  - Aggregate construction and operations (operations footprint being generally small compared to construction)

- **Ground-based observatories**

$$\text{Carbon footprint} = A_{\mathrm{co}} \times EF_{\mathrm{co}} + A_{\mathrm{op}} \times T \times EF_{\mathrm{op}}$$

  - Treat construction and operations separately (long lifetime of ground-based observatories)
  - Estimate dedicated emission factors

Greenhouse gas emissions versus cost



Carbon footprint reports of 19 French companies of the construction sector versus their turnovers (source: Base Carbone ADEME). The blue line corresponds to a monetary emission factor of 250 t CO_2e / M€, the light blue area indicates an uncertainty of 80%.

Activity Data

Mission	Payload launch mass (kg)	Mission cost (M€)	Reference
HST	11 110	8 037	43
Chandra	5 860	4 114	44
Cassini	5 820	2 806	45
Cluster	4 800	944	46
Fermi	4 303	863	47
INTEGRAL	4 000	419	48
Curiosity	3 893	2 590	45
XMM	3 800	1 113	49
Juno	3 625	1 082	45
Herschel	3 400	1 152	50
RXTE	3 200	360	51
SDO	3 100	865	52
Rosetta	2 900	1 709	53
Galileo	2 560	1 275	45
MAVEN	2 454	638	45
ROSAT	2 421	635	54
MRO	2 180	928	45
GAIA	2 034	1 037	55
Planck	1 900	775	56
SoHO	1 850	1 469	57
Suzaku	1 706		
AstroSat	1 515	27	59
MMS	1 360	1 054	58
Venus Express	1 270	300	61
WIND	1 250		
STEREO	1 238	614	60
Mars Express	1 223	374	62
Dawn	1 218	439	45
Hipparcos	1 140	933	63
Kepler	1 052	636	64
GEOTAIL	1 009		
Akari	952	106	65
Spitzer	950	1 188	66
SWIFT	843	279	67
ACE	752		
InSight	694	714	45
PSP	685	1 310	43
WISE	661	335	68
TIMED	660	259	67
Double Star	560		
IMP-8	410		
NICER	372	53	69
NuSTAR	360	156	70
TESS	325	275	71
GALEX	280	120	67
DEMETER	130	21	72

Observatory	Cost			
	Construction		Operations	
	(M€)	Reference	(M€ / yr)	Reference
VLT (Paranal)	1 384	78	40	79
ALMA	1 248	80	105	81
SOFIA	1 098	58	90	58
AAT	124	82	15	83
VLA	345	75	10	84
VLBA	132	85	15	85
IRAM	51	86	15	87
Gemini-South	135	75	13	75
CFHT	85	78	6.3	88
ESO 3.6m (La Silla)	99	89	5.2	89
GBT	120	90	10	91
LOFAR	200	92	9.2	93
JCMT	38	94	5.5	95
ATCA	95	96	3.5	97
H.E.S.S.	49	(1)	8.8	32
MeerKAT	128	98	13	98
GTC	125	78		
NRO	51	(1)	1.5	(1)
LMT	77	99	3.1	100
MLSO			1.2	101
APEX	20	(1)	2.7	102
SMA	60	103		
EHT	52	104	-	-
Noto Radio Observatory			1.5	105
2m TBL	6.0	(2)	1.0	106
2.16m (Xinglong Station)	7.3	(2)	0.7	(3)
1.93m OHP	5.5	(2)	0.5	(3)
KMTNet	17	(1)	1.7	(1)
THEMIS			1.1	(1)
2.4m LiJiang (YAO)	9.6	(2)	1.0	(3)
2m HCT (IAO)	6.1	(2)	0.6	(3)
1.5m Tillinghast (FLWO)	2.8	(2)	0.3	(3)
1.5m (OAN-SPM)	2.8	(2)	0.3	(3)
1.8m (BOAO)	4.6	(2)	0.5	(3)
1m (Pic-du-Midi)	1.0	(2)	0.1	(3)
1.3m Warsaw (OGLE)	2.0	(2)	0.2	(3)
C2PU	2.0	(2)	0.2	(3)
TAROT	0.9	(1)	0.1	(3)
1m NOWT	1.0	(2)	0.1	(3)

- Collection of payload mass data was easy
- Collection of cost data was the most time consuming part of this work
- Cost data not always include mission extensions and never include upgrades (**our results are lower limits to the truth!**)
- Use of parametric model for 1-2 m optical telescopes
- If no data were found then we skip contribution (even more lower limits)
- Cost data are often as confidential as carbon footprint data
- E-mail inquiries to get cost data were not often successful
- Sometimes needed to infer cost data by extrapolating from national contributions
- All cost data were inflation corrected to 2019 economic conditions

Results

Mission	Years	Papers since launch	Authors	Mass-based Footprint (t CO_2e)	Mass-based Annual ($\frac{t\,CO_2e}{yr}$)	Mass-based Carbon intensity ($\frac{t\,CO_2e}{paper}$)	Mass-based Carbon intensity ($\frac{t\,CO_2e}{author}$)	Cost-based Footprint (t CO_2e)	Cost-based Annual ($\frac{t\,CO_2e}{yr}$)	Cost-based Carbon intensity ($\frac{t\,CO_2e}{paper}$)	Cost-based Carbon intensity ($\frac{t\,CO_2e}{author}$)
HST	30	52 497	42 315	555 500	18 517	11	13	1 125 197	37 507	21	27
Chandra	21	17 714	23 942	293 000	13 952	17	12	575 955	27 426	33	24
Cassini	22	4 691	9 328	291 000	13 227	62	31	392 902	17 859	84	42
Cluster	20	2 433	2 959	240 000	12 000	99	81	132 207	6 610	54	45
Fermi	12	8 619	19 675	215 150	17 929	25	11	120 881	10 073	14	6
INTEGRAL	18	2 808	10 640	200 000	11 111	71	19	58 720	3 262	21	6
Curiosity	7	1 360	4 393	194 650	19 465	143	44	362 595	36 259	267	83
XMM	21	18 859	23 773	190 000	9 048	10	8	155 845	7 421	8	7
Juno	8	521	1 832	181 250	18 125	348	99	151 547	15 155	291	83
Herschel	11	5 046	11 092	170 000	15 455	34	15	161 238	14 658	32	15
RXTE	24	7 473	11 601	160 000	6 667	21	14	50 438	2 102	7	4
SDO	10	4 189	4 946	155 000	15 500	37	31	121 164	12 116	29	24
Rosetta	16	1 665	4 337	145 000	9 063	87	33	239 316	14 957	144	55
Galileo	30	2 432	4 594	128 000	4 267	53	28	178 503	5 950	73	39
MAVEN	6	672	2 023	122 700	12 270	183	61	89 270	8 927	133	44
ROSAT	30	19 765	23 154	121 050	4 035	6	5	88 844	2 961	4	4
MRO	14	1 927	4 261	109 000	7 786	57	26	129 850	9 275	67	30
Gaia	7	2 550	10 565	101 700	10 170	40	10	145 114	14 511	57	14
Planck	11	5 515	13 388	95 000	8 636	17	7	108 486	9 862	20	8
SoHO	25	12 218	12 955	92 500	3 700	8	7	205 617	8 225	17	16
Suzaku	15	3 869	9 525	85 300	5 687	22	9				
AstroSat	5	313	5 406	75 750	7 575	242	14	3 751	375	12	1
MMS	5	769	1 623	68 000	6 800	88	42	147 501	14 750	192	91
Venus Express	15	1 221	3 394	63 500	4 233	52	19	41 945	2 796	34	12
Wind	26	3 877	8 254	62 500	2 404	16	8				
STEREO	14	3 731	6 768	61 900	4 421	17	9	86 021	6 144	23	13
Mars Express	17	2 969	6 118	61 150	3 597	21	10	52 332	3 078	18	9
Dawn	12	791	2 175	60 885	5 074	77	28	61 409	5 117	78	28
Hipparcos	31	4 743	8 373	57 000	1 839	12	7	130 664	4 215	28	16
Kepler	11	4 306	9 606	52 620	4 784	12	5	89 037	8 094	21	9
Geotail	28	3 288	3 996	50 450	1 802	15	13				
Akari	14	2 037	6 993	47 600	3 400	23	7	14 878	1 063	7	2
Spitzer	17	9 050	15 940	47 500	2 794	5	3	166 333	9 784	18	10
Swift	16	7 397	17 307	42 150	2 634	6	2	39 030	2 439	5	2
ACE	23	4 147	7 560	37 600	1 635	9	5				
InSight	1	58	447	34 700	3 470	598	78	99 922	9 992	1723	224
PSP	2	287	1 075	34 250	3 425	119	32	183 456	18 346	639	171
WISE	11	6 990	18 877	33 050	3 005	5	2	46 855	4 260	7	2
TIMED	18	2 205	3 593	33 000	1 833	15	9	36 196	2 011	16	10
Double Star	16	166	540	28 000	1 750	169	52				
IMP-8	47	2 485	3 835	20 500	436	8	5				
NICER	3	338	2 657	18 600	1 860	55	7	7 374	737	22	3
NuSTAR	8	2 227	9 559	18 000	1 800	8	2	21 799	2 180	10	2
TESS	2	978	4 557	16 250	1 625	17	4	38 478	3 848	39	8
GALEX	17	5 452	13 790	14 000	824	3	1	16 780	987	3	1
DEMETER	16	422	1 014	6 500	406	15	6	2 907	182	7	3

- **Order of magnitude estimates** of lifecycle carbon footprints for 85 astronomical research infrastructures
- Annual footprints by dividing the lifecycle footprint by the mission or observatory lifetime (or ten years, whatever is longer)
- Results of individual infrastructures are uncertain by 80% (**carbon footprint of specific facility could be five times lower or almost two times larger!**)

Footprint attribution

- **How much of the research infrastructure footprint is to be attributed to IRAP?**
- **Two methods**
  - On the basis of the number of refereed papers co-authored by IRAP scientists
    - Compliant with metrics that are often used in evaluations
    - Adding-up attributions for different labs will exceed total carbon footprint of astronomical research infrastructures due to double counting
  - On the basis of the number of IRAP scientists that co-authored refereed papers
    - Provides the share of the footprint among the laboratories
    - Double counting only occurs for individuals with multiple affiliations