University of Pisa
Department of Computer Science
Ph.D in Computer Science

On Carbon Efficient Software Systems

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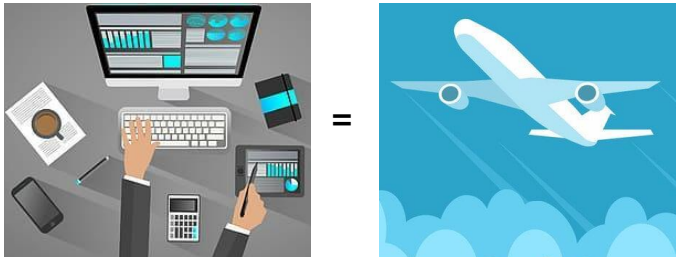
The need for Sustainable ICT and an EU perspective

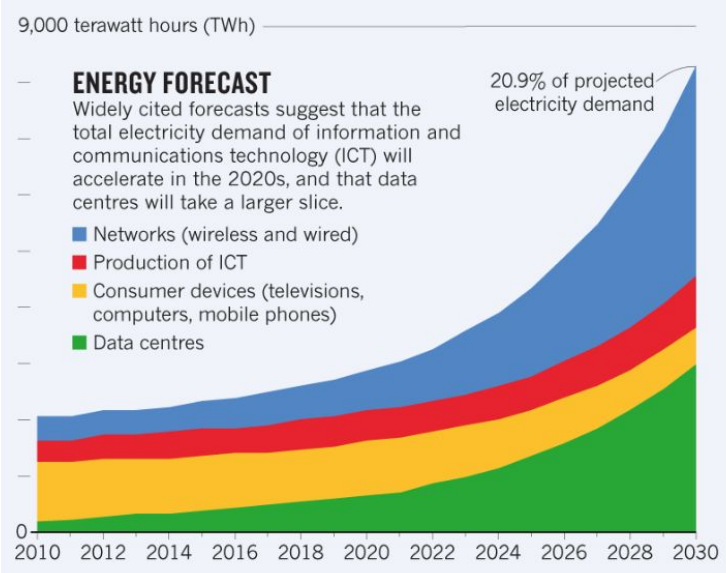
ICT is responsible of 2% of global CO2 emissions

(same as air traffic)



ICT energy consumption, currently between 6% and 9% of the world's total, is anticipated to rise to 20% by 2030.

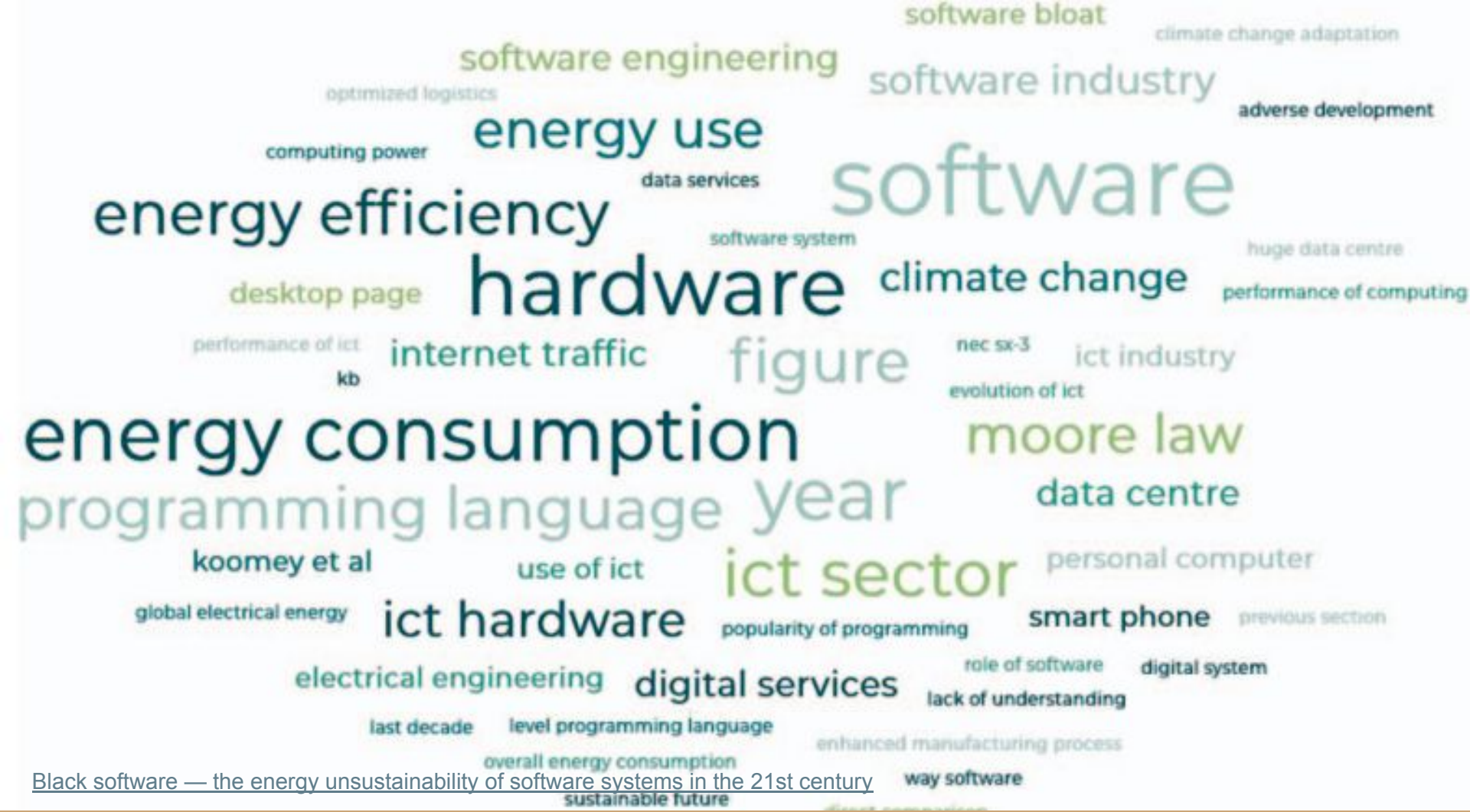
https://sdgs.un.org/2030agenda



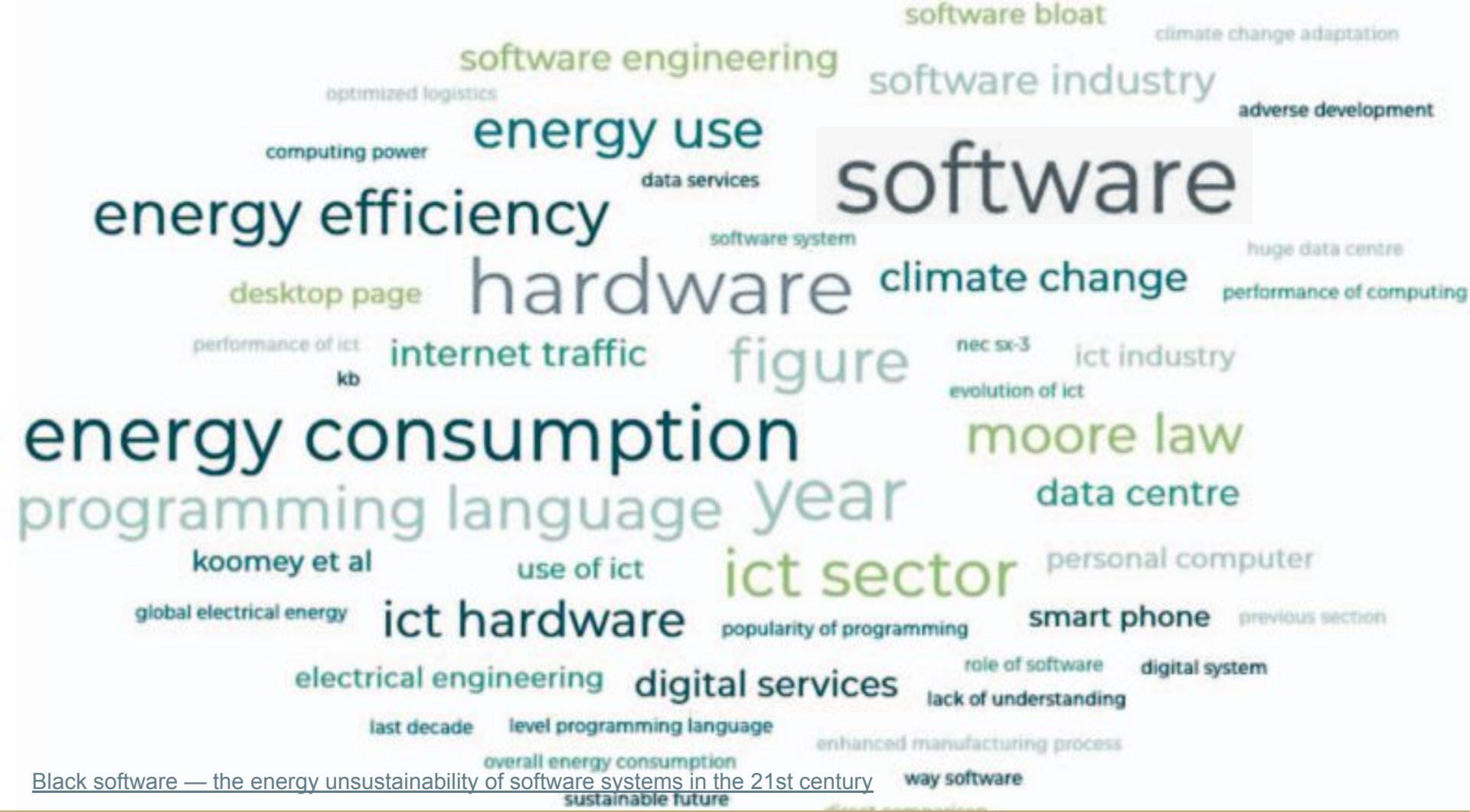
www.nature.com

The EU strategic agenda and industrial policy aim at

- building a climate-neutral, green, fair and social Europe
- targets the environmentally sustainable growth of the IT industry



Black software — the energy unsustainability of software systems in the 21st century



Black software — the energy unsustainability of software systems in the 21st century

Moore's Law
possibility of packing double the transistors in a chip

Reiser's Law
software is getting slower more rapidly than hardware bec

The software is fat!

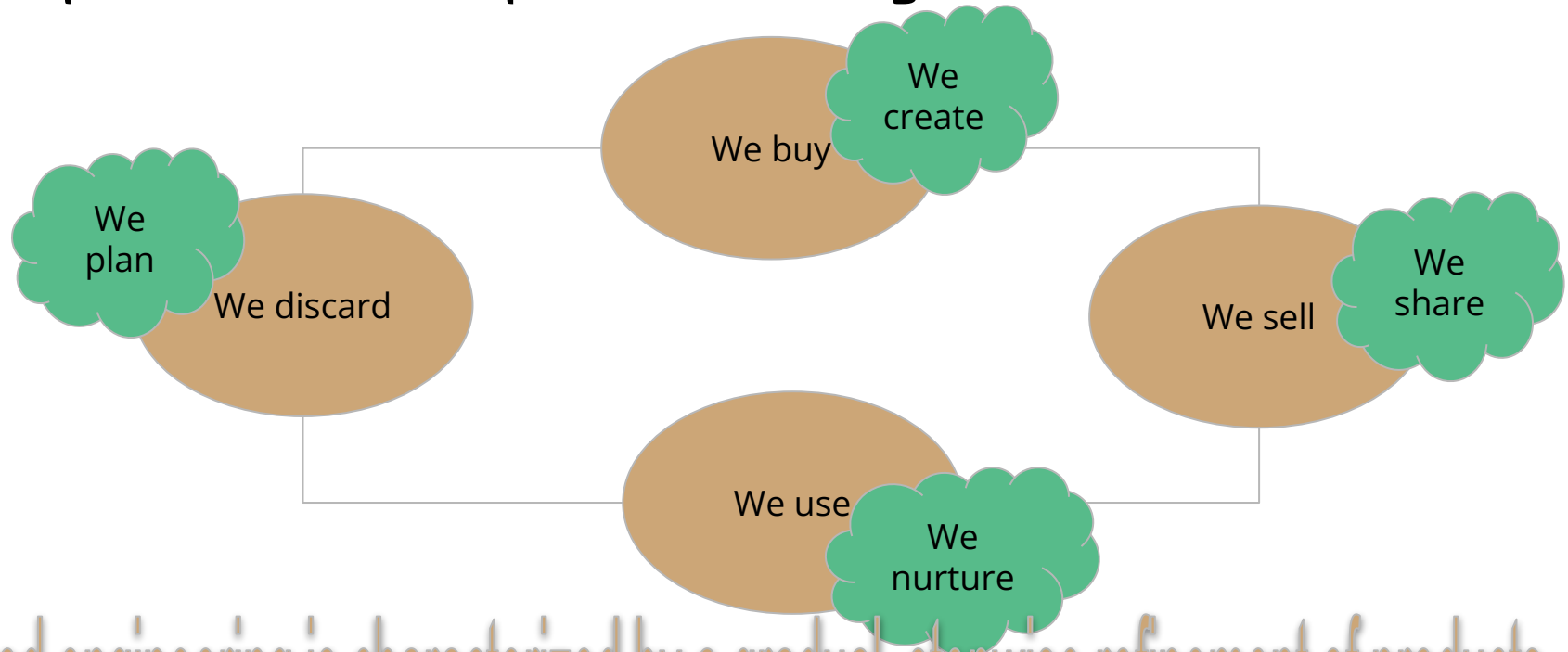
nson Law
expands to fill the available
emory

Windows 10

Wirth's Law
customer dependence is more profitable than customer education
A Plea for Lean Software

Windows 10,
Version 1903

Footprint vs. Handprint & Negative vs. Positive



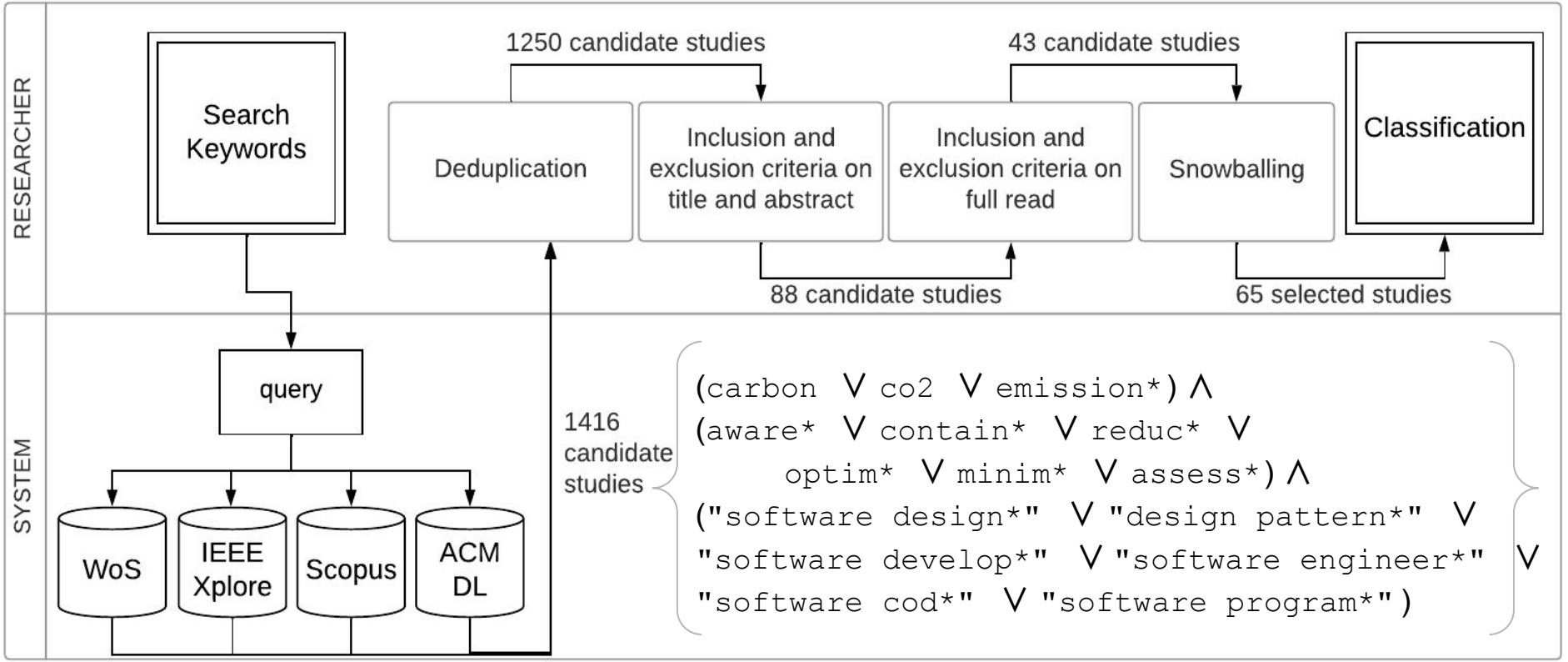
good engineering is characterized by a gradual, stepwise refinement of products

Topic

Which software engineering methodologies exist that support the design and development of sustainable carbon-efficient software?

- ❏ analyse the state-of-the-art in the field
- ❏ devise an original taxonomy to classify the identified literature corpus
- ❏ identify and discuss open research challenges and directions for future work

Methodology



State of the Art

There are a few surveys on different aspects w.r.t. the topic of this thesis:

Analyse older work
- Agarwal et al., 2012

Consider different life cycle steps
- Gaglianese et al., 2023
- Niina Hämäläinen, 2007

Consider business aspects of sustainability
- Ormazabal et al., 2014
- Muhammad Salam and Siffat Ullah Khan, 2016
- Arunasalam Sambhanthan and Vidyasagar Potdar, 2016

Consider different objectives
- Andrikopoulos et al., 2022
- Aryan Azimzadeh and Nasseh Tabrizi, 2015
- Khan et al., 2020
- Ahmadisakha and Andrikopoulos, 2024
- Castaño et al., 2023
- Heinrich et al., 2023
- Pop et al., 2023
- Popescu et al., 2022
- Abram Hindle, 2016
- Kim et al., 2021
- López-Pérez et al., 2022
- Didik Sudarmadi and Iwa Garniwa., 2023

5W1H - The devised taxonomy

WHO	Software Provider, Product Owner, Software Architect, Software Developer, Sustainability Engineer, IT operator, End User
WHAT	Sustainability Guidelines, Reference Models, Measurement Solutions, Software Improvement Techniques
WHY	Measure Energy, Reduce Energy, Minimise Energy, Measure Carbon, Reduce Carbon, Minimise Carbon
WHERE	Cloud Computing, Edge Computing, Mobile Applications, Blockchain, Cyber-physical Systems, Generic Software, Machine Learning, Computer Vision, High-performance Computing
WHEN	Requirements Analysis, Design, Implementation, Testing, Rollout
HOW	Publication Year, Publication Type


WHO
end user
IT operator
product owner
sustainability engineer
software architect
software developer
software provider
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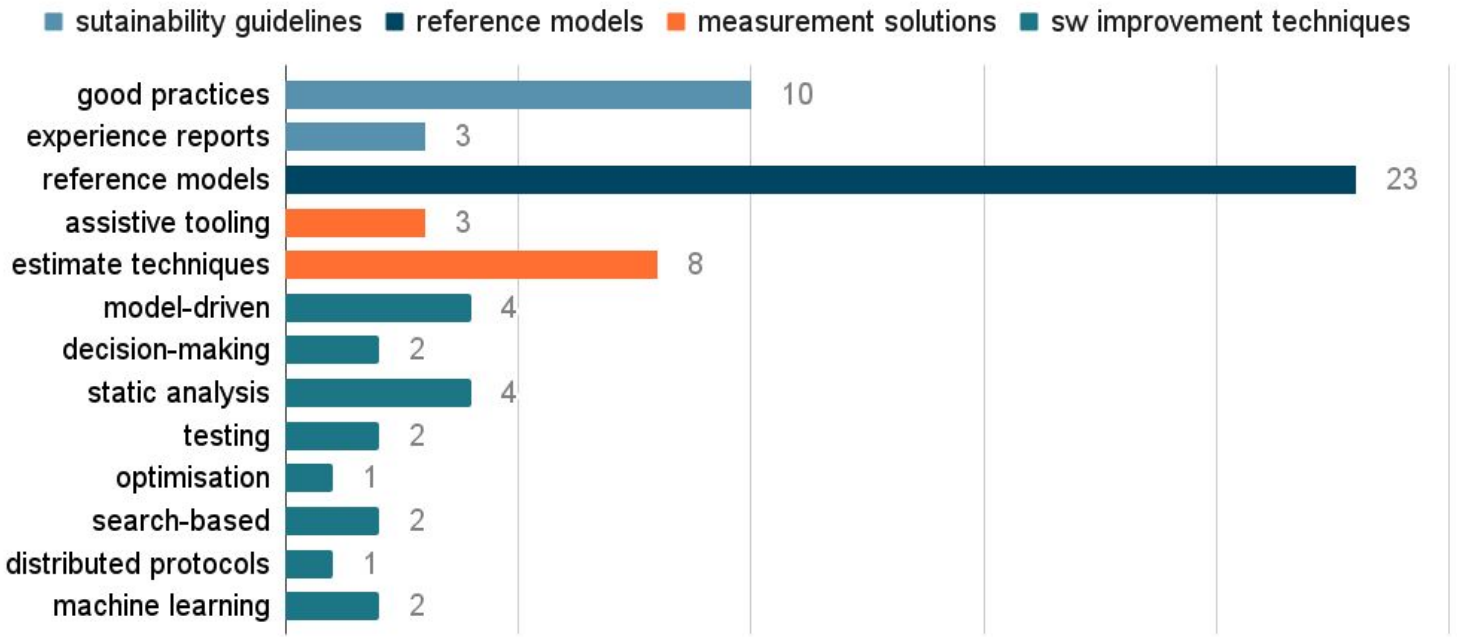
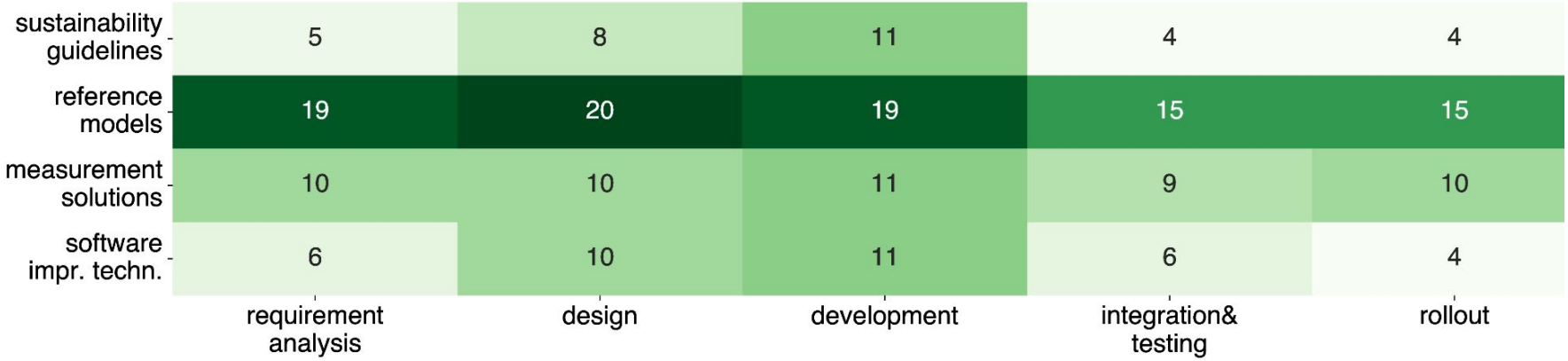
2
requirement analysis
design
development
integration& testing
rollout

WHAT


sutainability guidelines
reference models
measurement solutions
sw improvement techniques
good practices 10
experience reports 3
reference models 23
assistive tooling 3
estimate techniques 8
model-driven 4
decision-making 2
static analysis 4
testing 2
optimisation 1
search-based 2
distributed protocols 1
machine learning 2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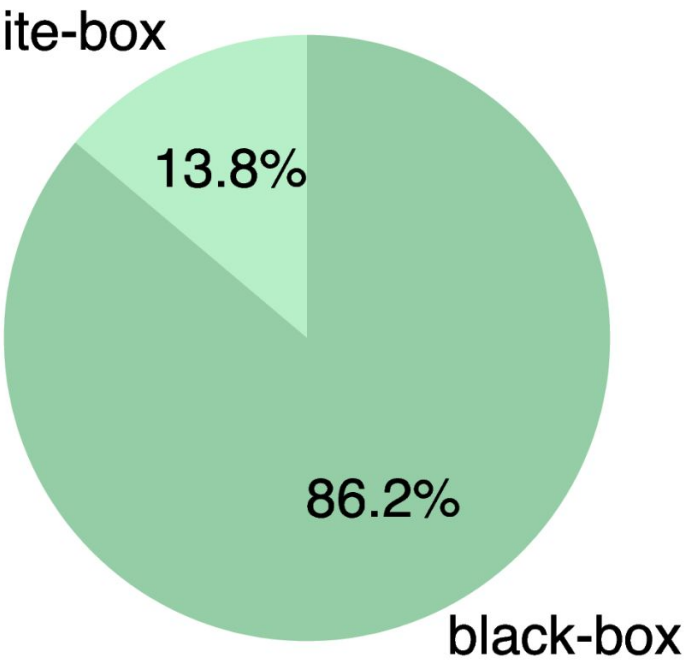
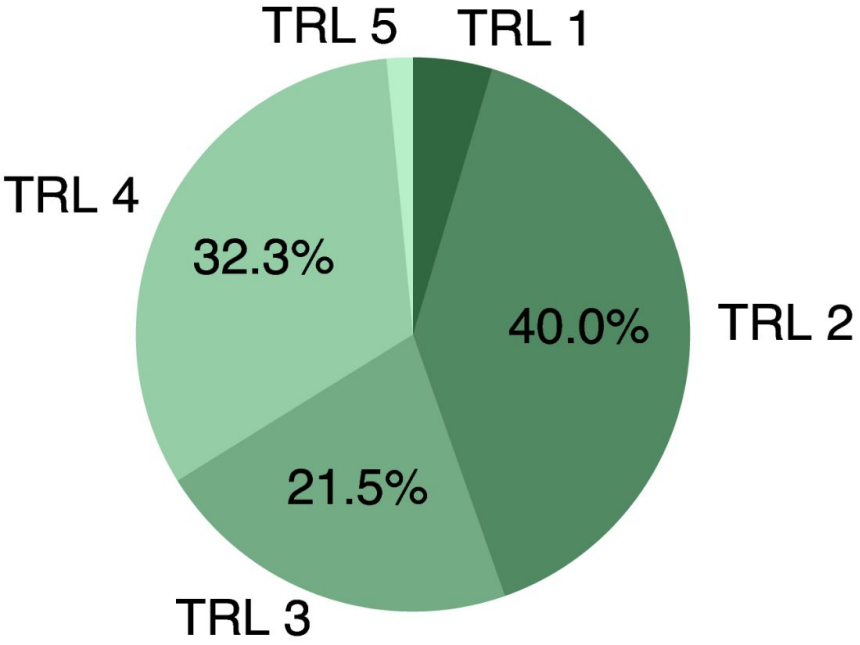
reference models 19 20 19 15 15
measurement solutions 10 10 11 9 10
software impr. techn. 6 10 11 6 4
requirement analysis
design
development
integration& testing
rollout

WHAT


white-box
13.8%
86.2%
black-box


TRL 5
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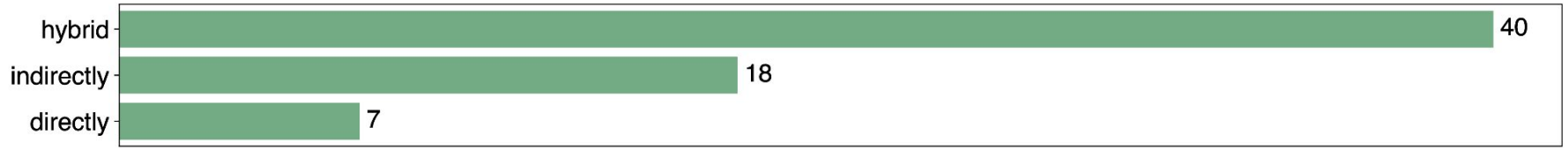
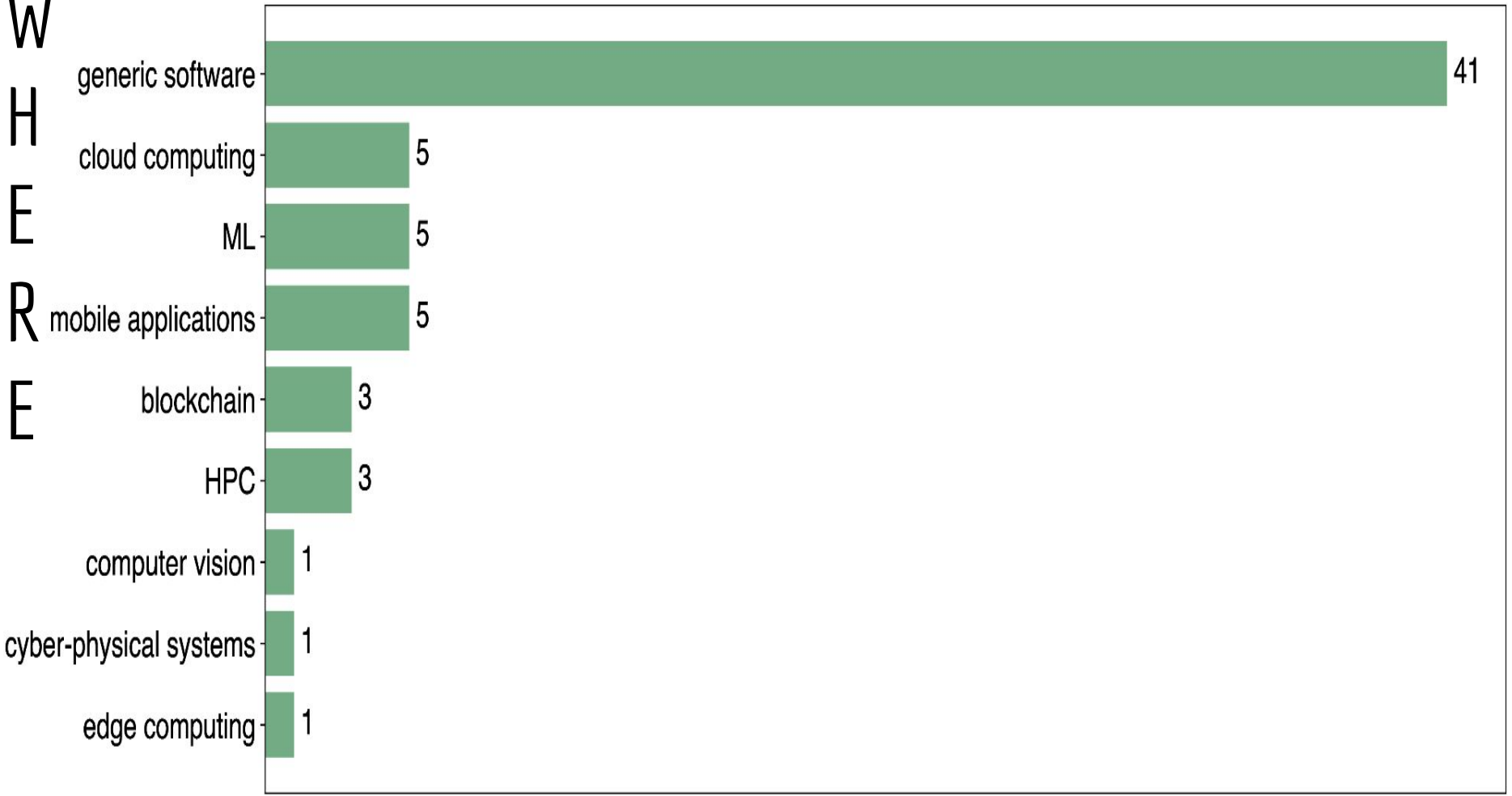
TRL 4
32.3%
40.0%
TRL 2
21.5%
TRL 3

WHY



	blockchain	computer vision	cloud computing	cyber-physical systems	edge computing	generic software	HPC	ML	mobile applications
indirectly measure	0	0	0	1	0	7	0	0	2
indirectly reduce	1	1	4	0	0	28	2	4	3
indirectly minimise	2	0	0	0	1	0	0	0	0
directly measure	0	0	0	1	0	5	0	0	1
directly reduce	0	1	5	0	0	23	1	4	2
directly minimise	2	0	0	0	1	0	0	0	0

WHERE


generic software
41
cloud computing
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ML
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mobile applications
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blockchain
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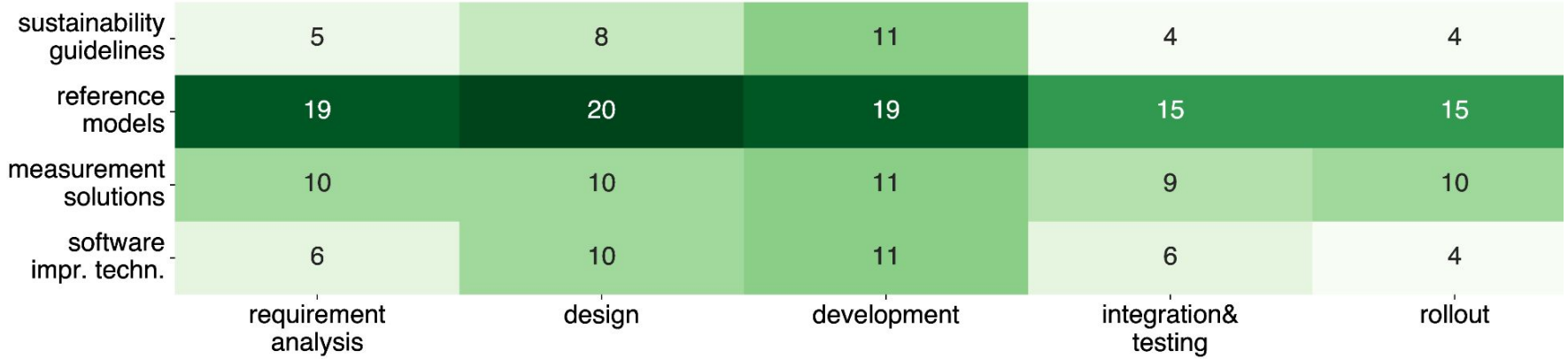
HPC
3
computer vision
1
cyber-physical systems
1
edge computing
1

WHEN


sustainability guidelines
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measurement solutions
software impr. techn.
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requirement analysis
design
development
integration& testing
rollout


requirement analysis
design
development
integration & testing
rollout
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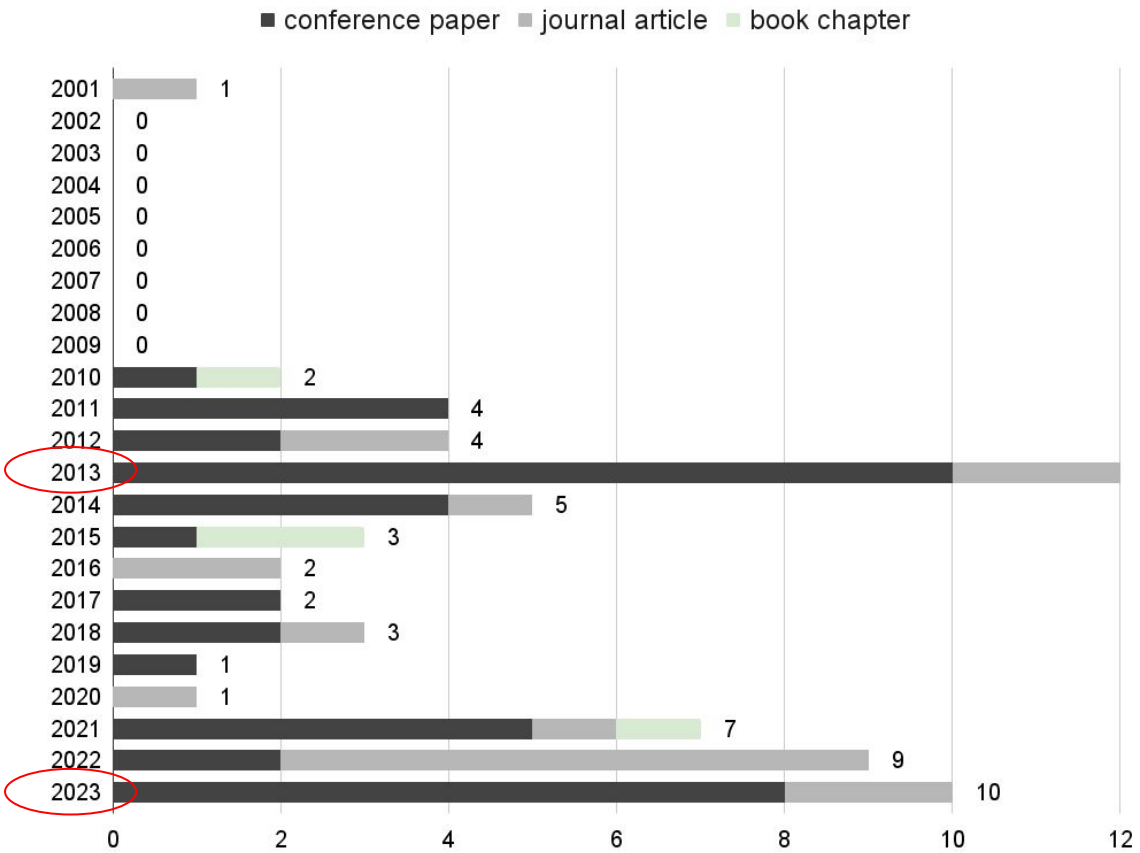
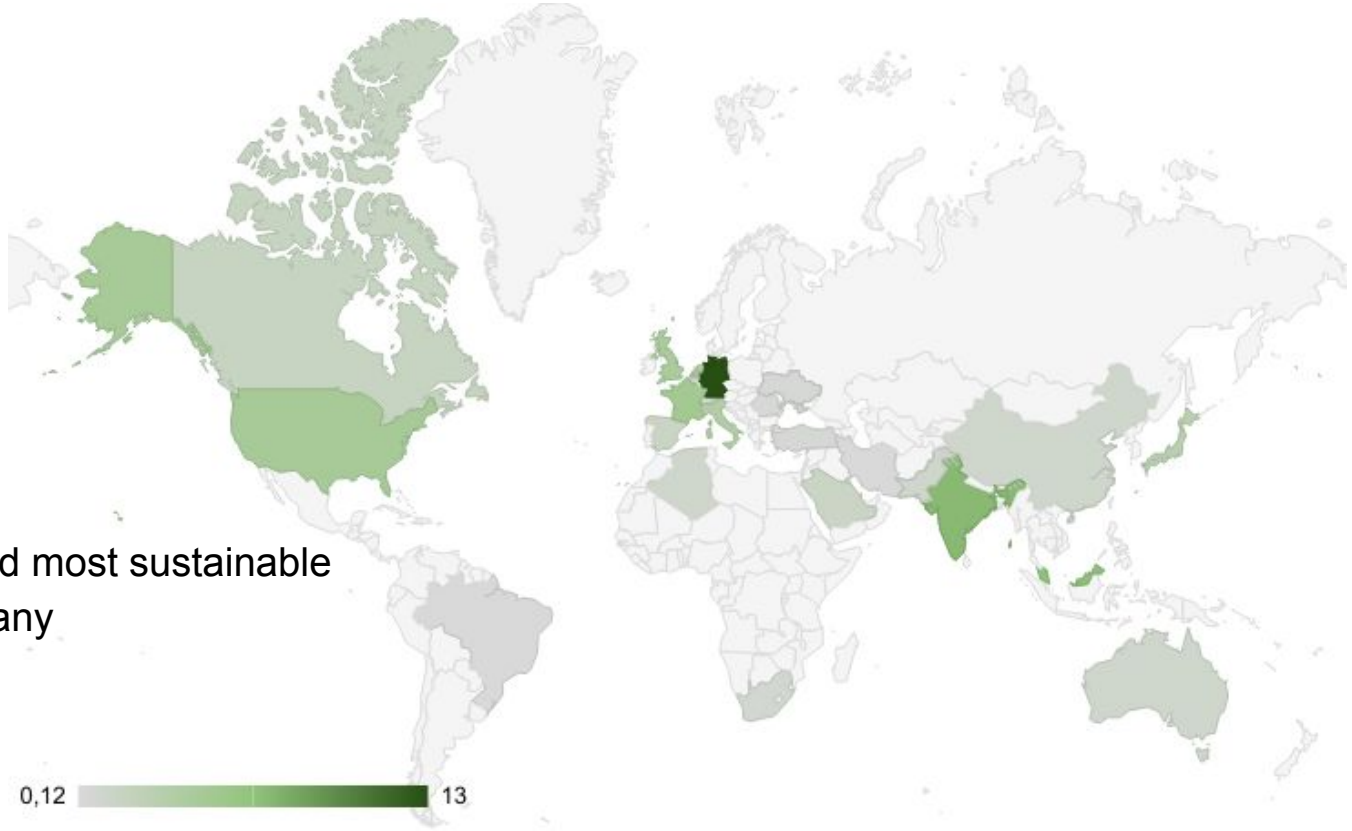


Most of the publications are motivated by early investments plans and have the same type of publication trend

HO
W



The greenest and most sustainable country is Germany

5W1H - Upcoming challenges

WHO	• support and assist all stakeholders
WHAT	• investigate white-box models • improve TRL by experimentation
WHY	• enhance the accuracy of measurements/estimates of carbon emissions • increase the carbon-awareness
WHERE	• adapt existing solutions onto target applications domains
WHEN	• adapt existing solutions to support all lifecycle steps

4 threats to SRL validity

EXTERNAL	resources lie on indexing platforms
CONSTRUCTION	generalizability of constructs
INTERNAL	validity of methods
CONCLUSION	reasonability based on available data

Concluding remarks

Which software engineering methodologies exist that support the design and development of carbon efficient software?

- ☑ analyse the state-of-the-art in the above field
- ☑ devise an original taxonomy to classify the identified literature corpus
- ☑ identify and discuss open research challenges and directions for future work

5W1H - Future Work

WHO

- support and assist all stakeholders

Reference Models

WHAT

- investigate white box models
- improve TRL by experimentation

Green Code Smells
Real...

Carbonshift!

WHY

- enhance the accuracy of measurements/estim... of carbon emissions
- increase the carbon-awareness

C... performa...e/c...t Parameter

WHERE

- adapt existing solutions onto target applications domains

Carbon-related Peculiarities

WHEN

- adapt existing solutions to support all lifecycle steps

Assistive Tooling

Thank you

Based on:

https://arxiv.org/pdf/2407.19901

This preprint is currently submitted for publication by an international journal.

Appendix

Ref.	WHO							WHAT			WHY					WHERE	WHEN					HOW	
											ENERGY			CARBON									
	sw provider	prod. owner	sw architect	sw developer	sust. engineer	IT operator	end user	proposal	white-/black-box	TRL	measure	reduce	minimise	measure	reduce	minimise	target application domain	req. analyses	design	development	testing	roll-out	publ. type	publ. year
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[S2]			✓		✓			sw improvement techniques	SE	B	4			✓		✓	blockchain			✓			J	2023
[S3]			✓		✓			sw improvement techniques	SE	B	4			✓		✓	blockchain			✓			J	2022
[S4]	✓	✓		✓			✓	reference models		B	3					✓	cloud computing	✓	✓				J	2014
[S5]	✓	✓		✓	✓			reference models		B	2		✓			✓	generic sw	✓	✓	✓			J	2016
[S6]				✓				sw improvement techniques	ML	B	4	✓					mobile app.	✓					C	2014
[S7]				✓				sustainability guidelines	ER	B	4		✓				ML		✓	✓			C	2021
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[S10]				✓	✓		✓	reference models		B	2		✓			✓	generic sw	✓	✓	✓	✓	✓	C	2013
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