Title: Powers of 10: a cross-scale optimization framework for rapid sustainability transformation

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Abstract: To achieve the goals of the Paris Agreement, strategic scaling of existing and emerging technologies and practices is imperative. A new "Powers of 10" (P10) logarithmic optimization framework presented here identifies potential optimal scales for implementing climate action strategies between a single individual and the globally projected ~10 billion persons by 2050. Applying a dataset of existing strategies from Project Drawdown, we find prioritizing community to urban-focused climate action strategies can complement top-down and bottom-up efforts and support rapid sustainability transformation.

One Sentence Summary: Prioritizing climate action strategies at community to urban scales (10K-1M) is key to addressing sustainability challenges.

Main Text:

INTRODUCTION

While there is almost unanimous international agreement to the aspirational goals of rapid reduction of greenhouse gases set forth in the Paris Agreement (*1*) and related initiatives such as the Sustainable Development Goals (SDGs) (*2*–*5*), the ability to translate these aspirations into reality is challenged by the need to effectively scale existing Climate Action Strategies (CAS), and quickly design, test and deploy emerging ones. CAS supported by relevant policy and economic instruments, often have multiple co-benefits, but their primary aim is, through anticipation and adaptation, to reduce human-caused climate risks, vulnerabilities and impacts e.g. the combustion of fossil fuels and the resulting release of greenhouse gases (*1*–*5*). However, often plans for deploying multi-scale CAS and related goals rely on relative and subjective terms such as "national", "state", "regional", "community", and "local" to frame the populations involved. Usage of such terminology lacks the precision necessary for strategic innovation and formulation of initiatives to deploy CAS that will lead to benefits such as carbon sequestration, cost savings, returns on investment, cleaner air and water, improved health, or heightened quality of family and community life (*3*).

Since the signing of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, efforts to address global warming and climate change have primarily focused on top-down, national government initiatives and experts (*3*, *6*). The Paris Agreement marked a shift away from rules-based governance towards goals-based governance, requiring innovative approaches to engage multiple sectors of society (*1*). However, well before the Paris Agreement, there were also scores of efforts to mobilize climate action in subnational and nongovernmental entities (*6*). Over the last two decades, as many universities, municipalities, states and corporations began to develop their own climate action plans or strategies, alliances and collaboratives have emerged, including the U.S. Climate Alliance (*7*), Pacific Coast Collaborative (*8*), C40.org (*9*), Mayors Conference for Climate Change (*10*) and Local Governments for Sustainability (*9*). Indeed, subnational engagement and alignment was viewed as essential by UNFCCC leadership leading up to the 2015 Paris Agreement, with the launch of the Non-State Actor Zone for Climate Action (NAZCA) platform at COP20 in 2014**,** and some have suggested that the announced plans for the U.S. to leave the Paris Agreement may prove to be positive by motivating other actors to step-up (*11*). Efforts to promote bottom-up climate action at individual scales through behavior change and consumer choices have also been proposed, which often take the form of "the top ten things you can do to stop global warming" such as becoming vegetarian, installing solar panels, having fewer children, flying less often, or advocating for specific economic incentives and interventions, such as carbon taxes (*12*, *13*).

As the field for global warming intervention broadens to recognize subnational efforts, the available metrics for scaling and measuring progress of CAS are misleading *(6)*. For instance, counting the number of nations rather than the total number of persons impacted, which may be orders of magnitude disparate in size, is fundamentally inaccurate (*14*). While nation states are accepted by the UNFCCC as the primary entities responsible for climate actions, with "common but differentiated responsibilities," among the 193 United Nations member states there is a range of more than four magnitudes (see Table S1 and methods in supplementary materials). The People's Republic of China and India are over a billion persons each, with the United States being about a third of their size. The average size of a sovereign nation in 2017 is an order of magnitude smaller than the United States at about 39 million, e.g. the size of Iraq or Poland. More importantly, the median is currently 8.8 million, the size of Israel or Tajikistan. Focusing on nation states without emphasizing their variable populations also obscures the fact that the 40 megacities with over 10 million inhabitants have a combined population of over 700 million, more than double the total of the nations at or below the median (Table S1).

To overcome this relative and subjective bias in the existing scales of CAS and help identify individual, proxy and collective agencies, and corresponding systemic and institutional dynamics at different scales, we present the "Powers of 10 (P10)" framework as a tool to discern optimal interventions for the strategic deployment of CAS, and the related economic and social instruments that will achieve economic benefits and carbon reductions at optimal scales. By using the ten orders of magnitude between a single individual and the projected ~10 billion global population by 2050 (*15*), we formalize population cohorts with a preliminary taxonomy to provide a higher level of precision for examining the number of persons living in a specific physical location, who will benefit from and may also implement specific CAS.

THE FRAMEWORK: FROM PERSON TO PLANET

The P10 framework employs exponent scaling (x^n, $x \in N$ and $n=0-10$) to frame ten orders of magnitude between a single individual and ~10 billion persons projected on the planet Earth by 2050 (Fig. 1). The framework yields 11 population cohorts, i.e. 10^0 - 10^{10} (P0 - P10), in which we aggregate and distribute the projected ~10 billion persons irrespective of the relative sizes of nations, communities, schools, and other traditional social institutions that often span several orders of magnitude. The number of persons in each P10 cohort represents a critical mass for forming "agency", which we define as the capacity to make decisions, influence actors and take actions at the appropriate scale (see methods in supplementary materials for details), to implement and benefit from the CAS first hand, with the social systems, structures and institutions at varying scales being integral for shaping, constraining or empowering agency. For example, the 10^0 cohort (P0 or 1 person) refers to individuals and couples; the 10^4 (P4 or 10,000 persons) cohort represents community-scale agency, such as small municipalities and large non-governmental organizations; and the 10^8 cohort (P8 or 100 million persons) are large nations, sub-continental areas or transnational entities.

We propose a P10 taxonomy analogous to the conventional social-geographic cohorts (Table 1), of which the median population sizes roughly correspond to respective P10 cohorts (Table S1) even though the population ranges may span over multiple P10 cohorts (Fig. 1). The variable sizes of education, enterprise and governance institutions are also represented by the ranges within the P10 cohorts (Table 1).

TESTING THE FRAMEWORK WITH CLIMATE ACTION STRATEGIES

We derived 72 CAS from Project Drawdown (PD) (*16*), which has conducted an in-depth and on-going analysis of 100 such existing and emerging strategies grouped in seven sectors: electricity generation, buildings and cities, transport, materials, food, land use and women and girls. We included a broad mix of CAS, of which some are well-known and currently being substantially up-scaled, e.g. wide deployment of renewable energy including wind and solar (*16*). Among the CAS examined are several that have strong potential but are less widely known or deployed, e.g. reducing food waste, silvopasture, and educating girls. We (and PD) excluded the CAS that are currently unfeasible at scale or lack rigorous analysis to assess their feasibility, such as bio-energy with carbon capture and storage (BECCS) or geoengineering schemes (*17*, *18*). We used the PD "Plausible scenario", which is the most conservative of three PD scenarios, projecting a total reduction of 1051 gigaton (Gt) carbon dioxide equivalent (CO_{2e}) during 2020-2050 against a reference scenario based on an assumption of frozen global emissions policy over the period 2015-2050 that is in line with the Intergovernmental Panel on Climate Change (IPCC) "business as usual" scenario. Roughly consistent with the 2015 Paris Agreement, the Plausible scenario could put the world on track to avoid dangerous climate impacts by 2050 (*19*, *20*).

The most appropriate P10 cohorts for implementing each of the CAS were determined through an iterative process involving the PD team, authors independently and then collectively. The PD team suggested cohorts were critically reviewed by the authors using related literature, real world examples and their professional expertise. The individual scores were combined and rated to arrive at the final set of P10 cohorts with the strongest authors' agreement, which were regarded as being the most suitable for the implementation of each CAS. The associated CO_{2e} reduction, cost and savings were then weighted across the P10 cohorts according to their span. Subsequently, the total CO_{2e} reduction, cost and savings for each P10 cohort by ranking and sector as well as for the geographic scale and transformation sphere were sub aggregated.

A working hypothesis for our study was that for many strategies there is a "sweet spot" around the midpoint between individual and global scales (roughly P5 or 100,000 persons), where local and global in a sense converge. Within this sweet spot, the collective ability to take meaningful (local) climate actions and the potential (global) impact of such actions are optimized (*21*). We identified sweet spots through the sectoral and systemwide medians of the P10 cohorts, across which the maximum number of CAS can be implemented. We also used two existing climate response frameworks to evaluate the scalability and feasibility of our P10 framework, i.e. a "regional sweet spot" for meaningful action and the impact of CAS (*21*), and the "transformation spheres" (*22*), where social transformation is depicted as a process taking place across embedded and interacting personal, political, and practical realms.

Overall, our aim with this analysis was to demonstrate the potential of the P10 framework using examples derived from the PD data and examine possible insights for practical application. Detailed data and methods are available in this article's supplementary materials. The technical details and references behind the PD analysis, which is on-going, are available on the Project Drawdown website (http://drawdown.org).

SWEET SPOTS FOR OPTIMIZING CAS IMPACTS

Our findings appear to confirm the overall sweet spot hypothesis, although at a somewhat smaller scale than anticipated (Fig. 2). The systemwide optimum (median) cohort for interventions is P4 (community, Fig. 2), which is a collective agency of 10,000 persons. This cohort scale optimizes the highest reduction (179 Gt) of CO_{2e} concentrations and offers the highest number (56) of implementable CAS. The CAS implementable at the sweet spot span every sector and includes all CAS from the land use sector (Table 2). However, the highest financial benefit (~10 trillion USD) from climate actions is obtained at P5 (metacommunity of 100,000 persons), compared to ~8 trillion USD at the systemwide sweet spot (P4). This implies that the community scale is where the majority of CO_{2e} reduction can be most effectively incubated and scaled (Fig. 2, Table 2).

Given the targeted reduction in carbon budget of 1051 $GtCO_{2e}$ in the PD Plausible scenario during 2020-2050, we find that almost half (46%, 480 Gt CO_{2e}) can be obtained across the P4 to P6 cohorts, along with 64% of the total benefit achieved (Fig. 2, Table 2). P4 to P6 also represent the top three cohorts for the net CO_{2e} reduction and climate action benefits (Fig. 2, Table 2). Hence, we suggest that prioritizing community to urban (P4 to P6)-focused climate action strategies may likely complement and amplify global top-down and local bottom-up efforts to support rapid sustainability transformation. Furthermore, our results suggest that the Paris Agreement, and potentially the SDGs and related treaties, initiatives and coalitions, may achieve the greatest level of impact in the sweet spot between P4 and P6 (community and urban) cohorts and their related social and governance systems to maximize the net CO_{2e} reduction and benefits from CAS.

Regarding the sweet spots for sectors, we find medians ranged from a low of P2 (personal network of 100 persons) for women and girls to a high of P5 (metacommunity of 100,000 persons) for energy and land use sectors (Table 2). The sweet spots for the largest sector (food, 30.66% of the total reduced CO_{2e}) and the smallest (transport, 4.36% of the total reduced CO_{2e}) sector are P4 (community of 10,000 persons) and P3 (village of 1,000 persons), respectively. Consequently, while the broad sweet spot for implementation across the globe exists between the scales of 10,000 (P4) to 1,000,000 (P6) persons, different sectors and locations will need to determine their own ideal practical range to deploy the greatest number of appropriate and implementable CAS to reach the highest net CO_{2e} reduction and financial benefits for their population size (*23*, *24*). Even as larger-scale policies and financial support are vital for maximizing economies and sublinear efficiencies of scale (*25*), our initial findings suggest that a distributed and localized approach in the P4 - P6 range is likely the key for scaling CAS at the rate needed for halving gross anthropogenic CO_{2e} emissions every decade in order to meet or exceed the Paris Agreement target (*26*, *27*).

GEOGRAPHIC SCALES, TRANSFORMATION SPHERES

We find that the "local" cohort in the "regional sweet spot" optimization framework (*21*), by their median population, span across P0 (individual) to P6 (urban/region) cohorts (Fig. 3a). Likewise, the P7 (national) to P9 (continental) and ultimately P10 (global) cohorts roughly correspond to the "regional" and "global" cohorts, respectively. Moreover, in this initial investigation using PD plausible scenario data, we find a cumulative reduction of 853.23 Gt and 196.82 Gt CO_{2e} from the local and regional scales, respectively, while all 72 Project Drawdown solutions are implementable and/or influenced initiating at the local scale (Fig. 3a). Moreover, the net CO_{2e} reduction, number of CAS and benefits are substantially higher at the local scale than if implemented at the regional scale (Fig. 3a). This is because many of the readily adopted PD CAS with high CO_{2e} reduction and benefit (such as plant-rich diet, family planning, educating girls and regenerative agriculture) are implementable at the local scale, i.e. P0 - P6 (Table 2). The P10 cohorts at the regional scale (P7 - P9) can also make substantial contribution in climate solutions with CAS such as wind turbines and improvement of international freights and highspeed rail (Table 2), for which national and regional policy supports are crucial (7). This illustrates how the P10 framework adds nuance and rigor to helping define and characterize geographic regions now defined vaguely as "local" and "regional" and their interrelationship with other scales (*28*, *29*).

Regarding three "transformation spheres" (*22*), in general terms, we find the P0 (individual) to P2 (personal network) cohorts correspond to the personal sphere, where changes in norms, beliefs and mind-set take place, e.g. plant-rich diet (*30*) (Fig. 3b). This is also in line with Dunbar's insights into primate, including human, behavior, with generally between zero and five primary partner(s), perhaps 15 to 20 friends or intimate relationships, around 45-50 "best" or good friends, and up to 150 friends or "familiars" that make up our personal, active social network (*31*). A broad range of P10 cohorts, i.e. P3 (village) to P9 (continental), correspond to the political sphere, often with multiple layers of decision-making and governance impacting individuals and communities. The cumulative effects of transformation in the personal and political sphere are measured at the practical sphere (behavioral and technical responses) corresponding to the global (P10) cohort. We find that a net reduction of 241.82 Gt and 808.23 Gt CO_{2e} can be achieved through the transformation of personal and political spheres, respectively. Thus, we show that a higher net CO_{2e} reduction and benefit can be achieved in the political sphere, when multiple intersecting layers of government, social and economic interests and activities are represented and amplified (*30*).

DISCUSSION AND OUTLOOK

Our proposed P10 framework may help to spur and blend individual and collective agencies for innovations, decision-making, new policies, and climate action at scale by adding precision and reducing relativity in the range of social, economic and political power structures. For example, the decision to develop a city's bike infrastructure to reduce its transport sector emissions is made by the local authority and embedded in that particular city policy, but its usage and often its implementation are initiated or instrumented by the citizens, who will also benefit first hand from this CAS (*16*). Thus, while the scale of communities deploying bike infrastructures will vary several orders of magnitude, we estimate the median size to be around P5, or the metacommunity size of 100,000 persons (Table 2).

All CAS are context specific and dependent on factors, such as physical geography, climate, political instruments, public support, workforce availability and preparation and economic viability, for successful scaling (*32*). Thus, their range for deployment will span multiple P10 cohorts (Fig. 1), from individual efforts to reduce one's carbon footprint through consumer choice (*33*), transportation and household recycling (*34*, *35*), to the international scale initiatives such as the Kigali Amendment to the Montreal protocol (*36*), which manages potent hydrofluorocarbons and other heat-trapping gases. However, all CAS require sufficient numbers of persons to reach a "critical mass" of awareness and action to drive markets and policy, as well as to involve international agreements such as those to manage international shipping, or to protect forests and peatlands that sequester carbon and safeguard natural carbon sinks (*16*, *22*, *37*). P10 cohorts and their relative agencies will provide more precise quantitative analyses of potential CAS dissemination and related cascading effects by referring to the actual size of population involved (Fig. 1). Rather than relying exclusively on relative or subjective population statistics or jurisdictional terms and norms described above, policy makers, civic, education, financial and business leaders and others supporting CAS may use P10 to help clarify population cohorts to target appropriate innovations, interventions and other actions. This framework may also contribute to on-going sociological and psychological research, including agency and structures theory, as well as international relations scholarship.

The pace for scaling of CAS is clearly a significant challenge. There remains a substantial gap between emission reductions targeted and actual rate of reduction currently underway. The "carbon law" (*37*) calculates that carbon emissions must be cut in half each decade from now until the year 2050 to achieve this goal, i.e. an exponential decay curve that provides a measure of the required speed and scale for action. We propose that the P10 framework for scaling CAS across society can assist in targeting optimal interventions and tailoring relevant narratives, thereby helping address the urgency of implementing CAS interventions in order to rapidly reduce greenhouse gas concentrations.

The geographic scales for climate response admittedly cover a range that may span geographic areas of the planet inhabited by populations of many orders of magnitude (*21*, *28*). For example, a mega-city may cover a small geographic area, while a sparsely populated region may be many orders of magnitude larger (*29*) (Table S1). The growing concentration of populations in relatively small spatial areas thus presents an inherent challenge. We conclude that nested decision-making and interventions through the P10 cohorts across geographic scales will result in both "inside-out" transformation from the individual to the global scales, and "from the middle out" impact, especially in the P4-P6 range (Fig. 1). Investing in and scaling climate solutions in the P4 – P6 scale, through businesses, governments, financial-investment, cultural and media, education, and college/university institutions in the P4 - P6 (10,000 to 1,000,000 persons) sweet spot appears to be particularly important (Fig. 3). Many, if not most climate actions at individual to community scales (P0 – P4) have the potential to cascade up to metacommunity and national levels, especially with appropriate funding and policies, helping disseminate benefits and engagement across other P10 cohorts in a cumulative and exponential manner. Ultimately, the cascade effects of policies, funding and deployment of CAS through engagement at the community (P4) to urban (P6) "sweet spot" range can act synergistically to the achievement of the goals of the Paris Agreement and beyond at the national, regional, continental and global levels.

Scaling of CAS across the P10 cohorts will require using multiple systems, transdisciplinary methods and a myriad of financial, economic, business, technological, educational and social innovations, as well as effective policy tools. As an illustration of CAS across scales, consider the fact that few individuals at any scale have the wherewithal to arrange for wind turbine arrays or solar farms, or to transform forestry and agriculture practices without technical support and wider community support and participation, e.g. the successful "Plant for the Planet" initiative (*38*). Visionary and skilled individuals and groups have and can provide leadership to find resources and locate the know-how to deploy initiatives at the P2 - P5 scale (*39*). Individual and collective leadership for authorities, financing and policies at larger P5 - P10 scales, i.e. municipal, state, national or international, can provide the means to support localized initiatives at the rate required and in ways that compliment other social priorities (*40*). The converging effect of transformation of various P10 cohorts in the personal and political spheres will generate measurable impact at the practical (global/P10) sphere (Fig. 3b). Indeed, the dynamics and the obstacles to maximize impact are complex. For example, an individual or household's decision to move toward or continue a plant-based diet, for example, may conflict with global trends for increased meat consumption (*30*). Yet, as household demand for meat alternatives increase in one part of the world, culinary innovations to provide culturally satisfying plant-based protein options along with related policies highlighting health, economic and environmental benefits emerge, potentially shifting markets and reducing carbon dioxide emissions in all parts of the world.

An important next step will be to develop short term (e.g. two year) and decadal strategies that identify barriers and opportunities to increase CAS agency in persons and systems through "public awareness, education and engagement" as called for in article 12 of the Paris Agreement (*1*). Our findings suggest that efforts to optimize climate literacy, empowerment, capital deployment, and action in order to rapidly scale CAS should take into consideration how scales overlap and interact but generally focus at the sweet spot between the range of P4 (10,000 persons) and P6 (1,000,000 persons). We demonstrate an example case of how the P10 framework and PD CAS can be applied between the range of P4 and P6 scales in the supplemental material.

To conclude, the new P10 framework has the value of being flexible and adaptable enough to serve as a tool for cross-scale analysis, providing perspective on the structures and systems, obstacles and opportunities that are required for optimizing agencies for climate action and sustainable practices. While all scales are important to achieve success, we show that prioritizing community to urban-focused CAS is the single most important evidence-based paradigm shift we can take to support rapid greenhouse gas reductions, carbon sequestration and progress towards attainment of the Paris Agreement and SDGs.

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Figure and Table captions

Fig 1. The proposed "Powers of 10 (P10)" framework exhibiting 10-degrees of magnitude between an individual (10^0) and the projected global population by 2050 (10^{10}), which provides a mental model adding perspective to the broad continuum that connects one individual to all of humanity. The cohort names are analogous to the conventional taxonomy for individual to global cohort groups or organizations (see Table 1 for details).

Fig 2. Numbers of implementable climate action strategies (CAS), effective net carbon dioxide equivalent concentration (CO_{2e}) reduction and benefit (savings - cost) from climate action at 0 - 9 powers of 10 (P10) cohorts.

Fig 3. Adaptability of the powers of 10 (P10) framework in the (a) "regional sweet spot" and (b) "transformation spheres" frameworks. The P10 cohorts cumulatively reduce carbon dioxide equivalent concentrations (CO_{2e}) and benefit geographic cohorts and transformation spheres through the implementation of climate action strategies. Transformation in the personal sphere can support zero- or low-carbon lifestyles and behaviors, with cascading effects into the political and ultimately practical-global spheres as individual demands multiply exponentially to shape large scale supplies, products and services (Figure 3b). Note: the effective net carbon dioxide equivalent concentration (CO_{2e}) reduction and benefit (savings - cost) from climate action at the global cohort and practical sphere are the sum aggregates of local and regional cohorts, and personal and political spheres, respectively.

Table 1. Taxonomy and description of the Powers of 10 (P10) cohorts. The proposed taxonomy titles are necessarily relative and imprecise, with the order and degree of magnitude being the key for measuring and optimizing scaling.

Table 2. Project Drawdown (PD) climate action strategies (CAS, solutions) that have been included in our analysis. The grey highlighted CAS are implementable at the sweet spot (P4). The CAS are grouped into sectors previously determined by PD. We assigned ranges of Powers of 10 (P10) cohorts for each CAS and calculated median of the assigned cohorts for each CAS and sectors. The net carbon dioxide equivalent concentration (CO_{2e}) reduction and benefit from those CAS and sectors are extracted and calculated using the "Plausible Scenario". Negative benefits indicate losses when compared to fossil fuel-based system or when CAS were not implemented during the 2020-2050 period. However, this may be different when calculated for the lifetime of a CAS, e.g. insulation, which becomes a net financial benefit as a result of lifetime operational savings after 2050 but has a high prior cost. N/A values for net benefit indicate that high geographic and sectoral variability inhibited the calculation or they were calculated in other CAS. For technical details on the drawdown models, data, assumptions and procedures, readers are referred to Hawken (2017) *(16)* and the Project Drawdown website: www.drawdown.org.

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Figures

Fig. 1

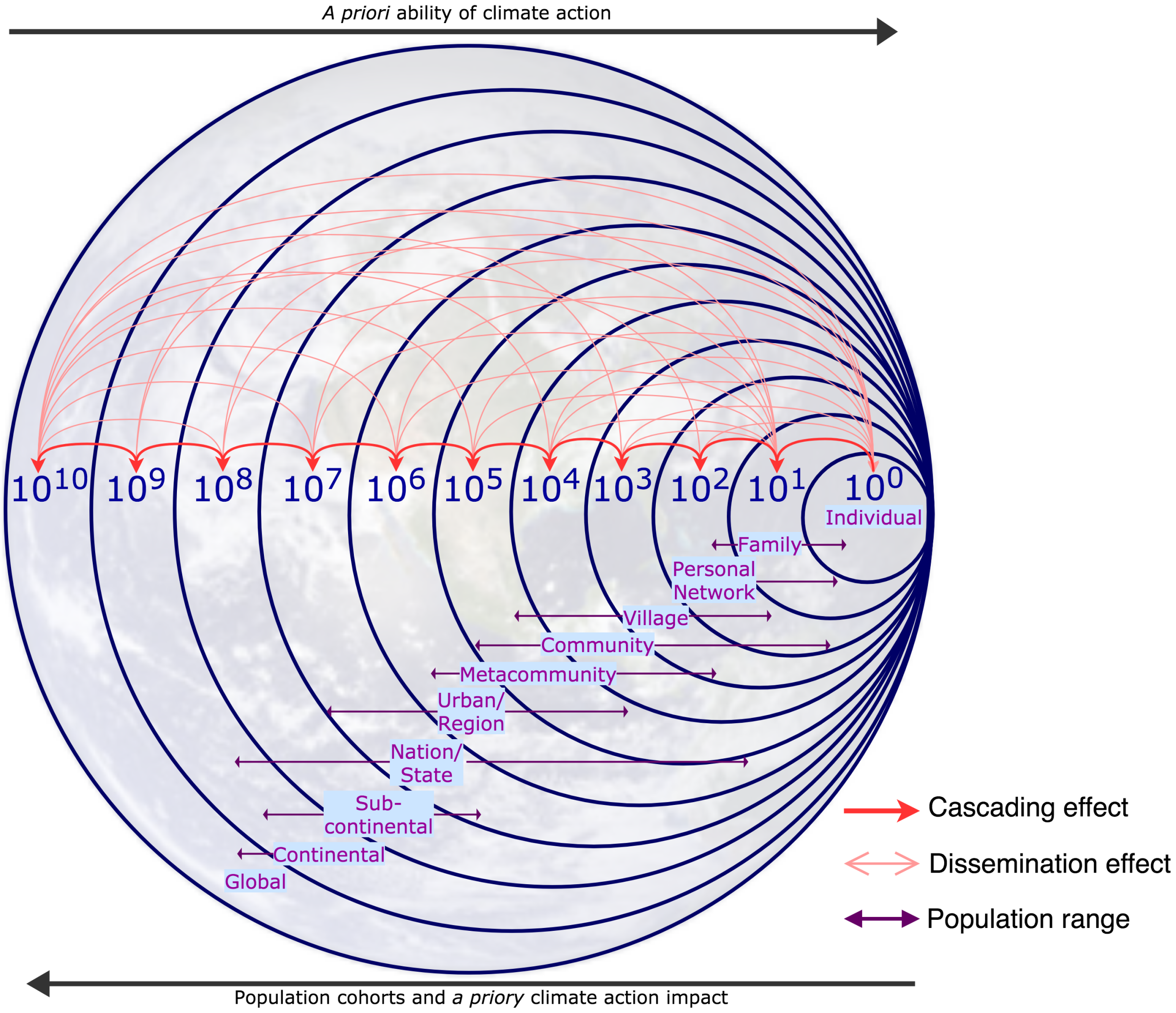


Fig. 2

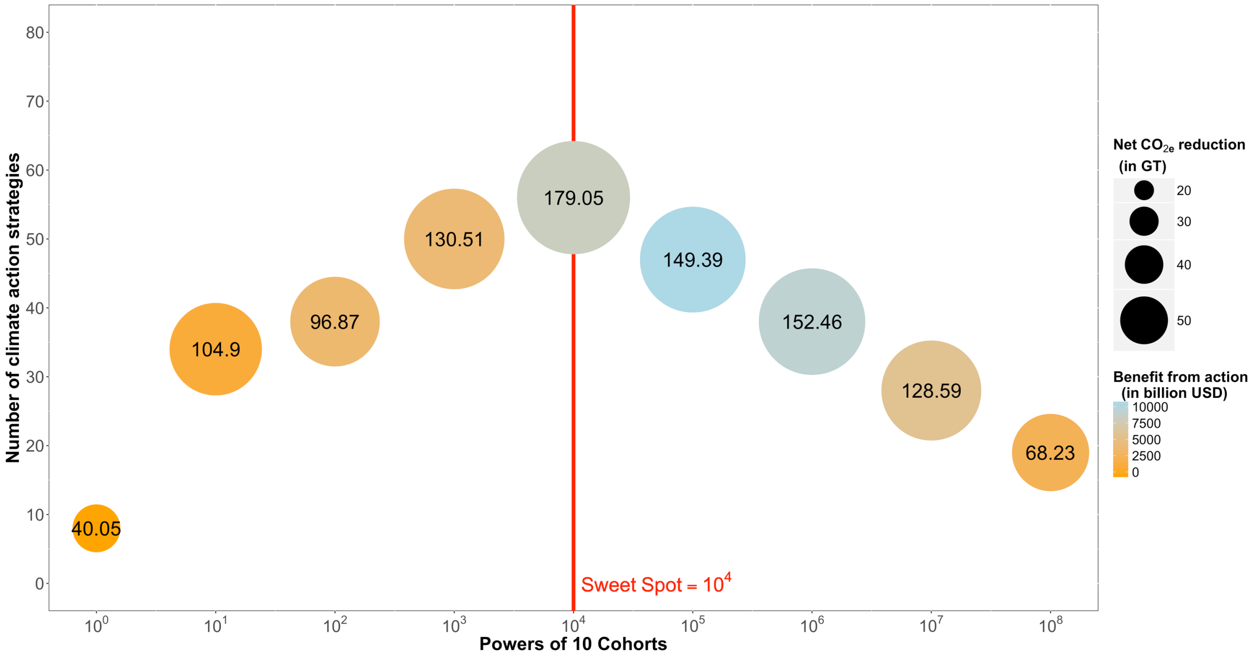
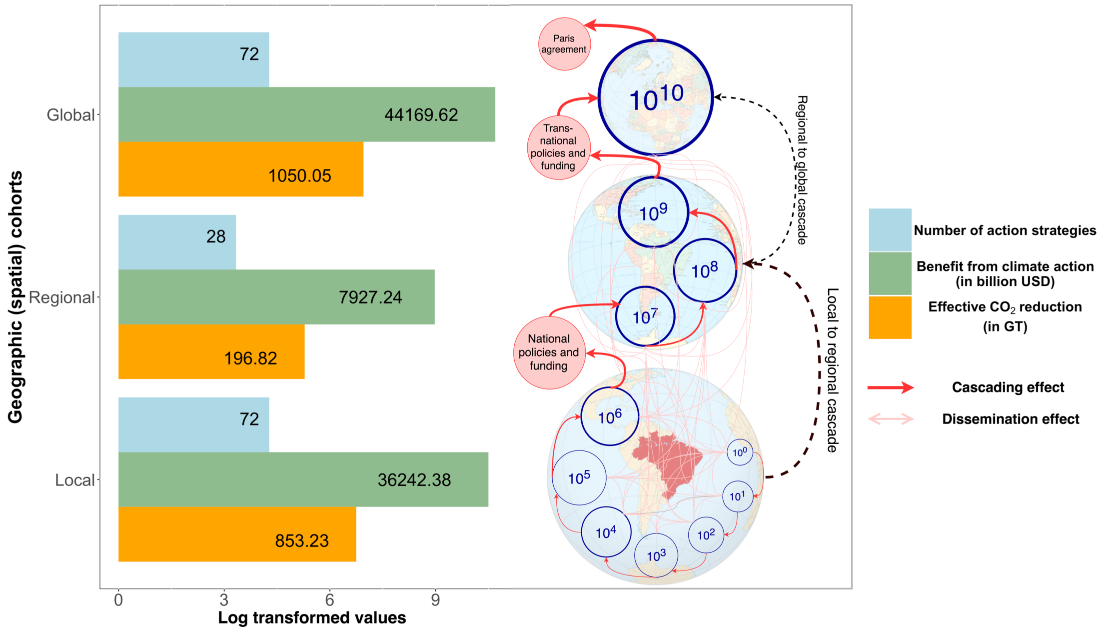
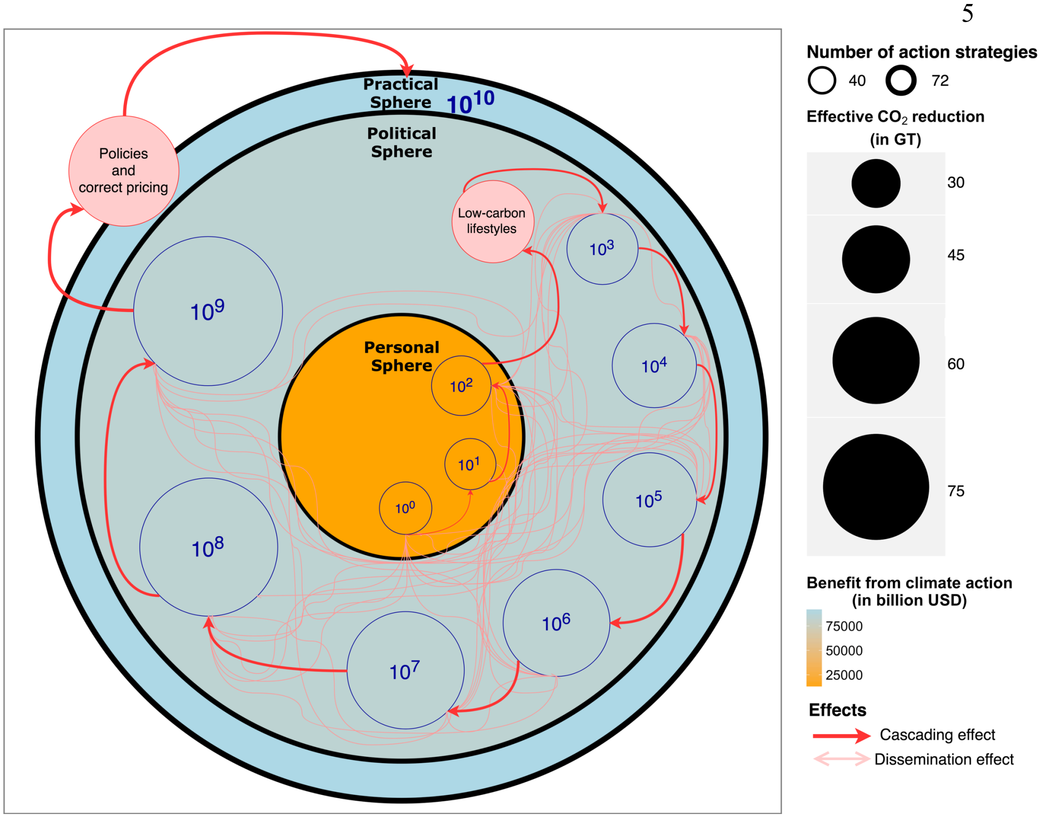

Number of climate action strategies
80
70
60
50
40
30
20
10
0
40.05
104.9
96.87
130.51
179.05
149.39
152.46
128.59
68.23
Sweet Spot = 10^4
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Powers of 10 Cohorts
Net CO_{2e} reduction (in GT)
20
30
40
50
Benefit from action (in billion USD)
10000
7500
5000
2500
0

Fig. 3

(a)


Geographic (spatial) cohorts
Global
72
44169.62
1050.05
Regional
28
7927.24
196.82
Local
72
36242.38
853.23
0
3
6
9
Log transformed values
Paris agreement
Trans-national policies and funding
National policies and funding
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
Regional to global cascade
Local to regional cascade
Number of action strategies
Benefit from climate action (in billion USD)
Effective CO_2 reduction (in GT)
Cascading effect
Dissemination effect

(b)


5
Practical Sphere
10^{10}
Political Sphere
Personal Sphere
Policies and correct pricing
Low-carbon lifestyles
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
Number of action strategies
40
72
Effective CO_2 reduction (in GT)
30
45
60
75
Benefit from climate action (in billion USD)
75000
50000
25000
Effects
Cascading effect
Dissemination effect

Tables

Table 1

Cohort	**Population Size**	**P10 Cohort**	**Proposed Taxonomy (Name: Entities)**
10^0	One	P0	Individual: each person on the planet
10^1	Ten	P1	Family: couples, households of all types and sizes, close friends, micro-business
10^2	One Hundred	P2	Personal Network: extended family, near neighbors, peers at school/work, small-medium businesses, social network
10^3	One Thousand	P3	Village: rural towns, large urban neighborhoods and schools, colleges, farms
10^4	Ten Thousand	P4	Community: small municipalities, large companies, suburbs, universities
10^5	One Hundred Thousand	P5	Metacommunity: set of interacting communities, mid-sized municipalities, large enterprises
10^6	One Million	P6	Urban/Region: urban areas and cities, workforce of largest multinational entities, regional governments
10^7	Ten Million	P7	Nation/State: megacities, states, nations, bioregions (e.g. Puget Sound)
10^8	One hundred million	P8	Sub-Continental: transnational and sub-continental jurisdictions, entities or areas
10^9	One billion	P9	Continental: continental and multinational entities or areas
10^{10}	Ten Billion	P10	Global: global treaties, agreements and organizations

5

Table 2

Overall Rank	**Climate Action Strategies**	**Sectors**	**P10 Cohort Range**	**Median of the P10 Cohort Range**	**Projected CO_{2e} reduction by 2050 (in Gt (%))**	**Net economic benefit, 2020-2050 (billion USD)**
25	LED Lighting	*Buildings and Cities*	1-6	3.5	12.85	2700.7
28	District Heating		4-6	5	9.38	3086.43
31	Insulation		1-5	3	8.27	-1142.59
41	Heat Pumps		1-5	3	5.2	1427.95
43	Building Automation		2-5	3.5	4.62	812.43
51	Walkable Cities		3-6	4.5	2.92	NA
54	Smart Thermostats		1-2	1.5	2.62	714.26
55	Land fill Methane		4-6	5	2.5	69.39
56	Bike Infrastructure		4-6	5	2.31	2427.44
58	Smart Glass		2-4	3	2.19	-607.2
67	Water Distribution		3-7	5	0.87	765.74
69	Green Roofs		1-5	3	0.77	-404.83
	Aggregate Buildings and Cities		*1-7*	*4*	*54.5 (5.19%)*	*9849.72 (25.63%)*
1	Wind Turbines (Land and Ocean)	*Energy*	5-7	6	98.7	5901.8
8	Solar Farms		4-7	5.5	36.9	5104.44
10	Rooftop Solar		1-5	3	24.6	3004.49
18	Geothermal		5-7	6	16.6	1179.82
20	Nuclear		6-8	7	16.09	1712.52
24	Concentrated Solar		5-7	6	10.9	-905.85
27	Methane Digesters (Small and Large)		1-7	4	10.3	-53.78
30	Wave and Tidal		5-7	6	9.2	-1416.54

33	Biomass		3-7	5	7.5	117.04
39	Solar Water		1-4	2.5	6.08	770.66
46	In-Stream Hydro		3-5	4	4	365.83
48	Cogeneration		2-4	3	3.97	287.68
64	Waste-to-Energy		5-7	6	1.1	-16.18
72	Micro Wind		1-4	2.5	0.2	-16.22
	Aggregate Energy		*1-8*	*5*	*246.14 (23.44%)*	*16035.71 (41.73%)*
3	Reduced Food Waste	*Food*	0-4	2	70.53	NA
4	Plant-Rich Diet		0-1	0.5	66.11	NA
9	Silvopasture		1-8	4.5	31.19	657.78
11	Regenerative Agriculture		1-8	4.5	23.15	1870.88
14	Tropical Staple Trees		1-8	4.5	20.19	506.9
16	Conservation Agriculture		1-8	4.5	17.35	2081.54
17	Tree Intercropping		1-8	4.5	17.2	-124.89
19	Managed Grazing		1-8	4.5	16.34	684.79
21	Clean Cookstoves		1-2	1.5	15.81	94.12
22	Improved Rice Cultivation and System of Rice Intensification		1-8	4.5	14.47	NA
23	Farmland Restoration		1-8	4.5	14.08	1270.23
29	Multistrata Agroforestry		1-8	4.5	9.28	682.99
57	Composting		3-6	4.5	2.28	2.9
61	Nutrient Management		1-8	4.5	1.81	NA
63	Farmland Irrigation		1-8	4.5	1.33	213.51
68	Biochar		2-4	3	0.81	NA
	Aggregate Food		*0-8*	*4*	*321.93 (30.66%)*	*7940.75 (20.67%)*
5	Tropical Forests	*Land Use*	3-8	5.5	61.23	NA

12	Temperate Forests		3-8	5.5	22.61	NA
13	Peatlands		3-8	5.5	21.57	NA
15	Afforestation		2-4	3	18.06	968.41
34	Bamboo		2-4	3	7.22	216.29
37	Forest Protection		3-8	5.5	6.2	NA
40	Indigenous Peoples' Land Management		3-8	5.5	5.25	NA
49	Perennial Biomass		1-4	2.5	3.33	NA
50	Coastal Wetlands		3-8	5.5	3.19	NA
	Aggregate Land Use		*1-8*	*5*	*148.66 (14.16%)*	*1184.7 (3.08%)*
2	Refrigerant Management	*Materials*	2-6	4	89.74	NA
35	Alternative Cement		4-5	4.5	6.69	NA
44	Water Saving—Home		1-2	1.5	4.61	1727.68
45	Bioplastic		2-4	3	4.3	NA
52	Household Recycling		3-6	4.5	2.77	-295.79
53	Industrial Recycling		3-6	4.5	2.77	-295.79
66	Recycled Paper		1-4	2.5	0.9	NA
	Aggregate Materials		*1-6*	*4*	*111.78 (10.65%)*	*1136.1 (2.96%)*
26	Electric Vehicles	*Transport*	0-1	0.5	10.8	-4421.63
32	Ships		3-4	3.5	7.87	-491.55
36	Mass Transit		4-6	5	6.57	NA
38	Trucks		2-5	3.5	6.18	2238.09
42	Airplanes (Improvements)		3-5	4	5.05	2525.38
47	Cars (Hybrids, etc.)		0-1	0.5	4	2360.41
60	Telepresence		1-4	2.5	1.99	1182.87
62	High-Speed Rail		5-8	6.5	1.52	-739.19

65	Electric Bikes		0-1	0.5	0.96	119.32
70	Trains		3-5	4	0.52	-494.78
71	Ridesharing		0-1	0.5	0.32	NA
	Aggregate Transport		*0-8*	*3*	*45.78* *(4.36%)*	*2278.92* *(5.93%)*
6	Family Planning	*Women* and Girls	0-4	2	59.6	NA
7	Educating Girls		0-4	2	59.6	NA
59	Women Smallholders		1-2	1.5	2.06	NA
	Aggregate Women and Girls		*0-4*	*2*	*121.26* *(11.55%)*	*NA* *(NA)*
	Overall Aggregate		*0-8*	*4*	*1051.01* *(100%)*	*38425.9* *(100%)*

Supplementary Materials for

Title: Powers of 10: a cross-scale optimization framework for rapid sustainability transformation

Authors: Avit K. Bhowmik, Mark S. McCaffrey, Chad Frischmann, Owen Gaffney, Abigail M. Ruskey

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This PDF file includes:

Materials and Methods

DATA: PROJECT DRAWDOWN

As the first effort to comprehensively aggregate, summarize and rank the top strategies, Project Drawdown (PD), an independent initiative, has compiled peer reviewed and widely cited literature of a diverse array of climate action strategies (CAS) and modeled their potential ability to reduce carbon dioxide equivalent (CO_{2e}) emissions and atmospheric concentrations, and associated costs and savings *(15)*. The book published in 2017 "Drawdown: The Most Comprehensive Plan Ever Proposed to Reverse Global Warming", edited by Paul Hawken, provides the context of the project and summary narratives of each of the strategies *(15)*.

While some attempts have been made to examine the technical feasibility of rapid and radical emissions reductions, such as the Deep Decarbonization Pathways Project and the Obama Administration's United States Mid-Century Strategy for Deep Decarbonization *(4)*, these and similar studies by other nations offer only the general outline of critical technologies and strategies to achieve substantial reductions by 2050, focusing in general terms on transitioning to a low-carbon energy system, cutting energy waste, ramping up renewable sources of electrical generation, sequestering carbon through forests, soils, and carbon dioxide removal technologies. Many such decarbonization analyses rely on unproven and controversial strategies, such as the use of bioenergy with carbon capture and storage (BECCS) *(16)*. PD's scope is similarly broad but more granular in detail than these related efforts, examining only existing strategies with sufficient literature and data to properly study, thereby omitting BECCS and large-scale geoengineering projects *(15)*. Building off a foundation of over 5,000 references, citations and sources, Drawdown focuses on the 82 primary current CAS being deployed as well as 20 additional "coming attractions" that show potential for wide deployment within the coming years but currently lack sufficient data to effectively model.

PD's reference emission scenario (RES) over 2015-2050 was developed using the average global greenhouse gas projections from 11 AMPERE models that adopted the reference policy scenarios assuming frozen global emissions policy over the period 2005-2050 *(41)*. The reference policy scenarios were designed to match the non-binding emissions reduction pledges and resulting policies made by several major emitters in the Copenhagen Accord of 2009 *(42)*. The emissions calculated in the RES do not include any additional effect of the land and ocean carbon sinks due to the very high variability and uncertainty in the processes and the amounts of carbon that are absorbed annually. However, the land sink is effectively modeled in solutions that allow sequestering carbon via plant biomass *(15)*.

The PD analysis focuses on seven sectors: Energy, Food, Women and Girls, Buildings and Cities, Land Use, Transport, and Materials *(15)*. A team of research fellows conducted an in-depth analysis of existing peer reviewed literature, and modeled three scenarios, i.e. Plausible, Drawdown and Optimum, of the top 76 (of 82) CAS that had sufficient data to effectively model against the RES *(15)*. The remaining six CAS could either not be modeled because of their high geographic and sectoral variability or their potential for CO_{2e} reduction, cost and savings have already been calculated in other CAS. The 20 "coming attractions" were also excluded from models due to insufficient data and high uncertainty. The findings were then reviewed by other experts and summarized in the book and website: www.drawdown.org. As a scientific enterprise, PD continues to review and update its findings based on new input and insights.

The CAS examined and modeled by PD span a range of scales, which were not explicitly established *(15)*. Some, such as rooftop solar, can be deployed at the individual and household level, while others require some degree of international cooperation and coordination, such as refrigerant management. The majority, including some of the most effective are somewhere in the middle, span local to national scales relative to their current or potential implementation and up-scaling. Many involve supply and value chains that may stretch far beyond the local level and in some cases rely on global connectivity. Virtually all involve complex social systems, including governance, finance, religious, cultural and secular values and face a range of related barriers, but if structural and systemic obstacles can be quickly identified and overcome, their potential is vast *(6,23)*. By localizing the context and identifying new career or entrepreneurial pathways of the community-appropriate strategies, such strategies can be properly scaled and their potential maximized.

For the purposes of this analysis, we used the July 2017 dataset relating to the Plausible scenario provided by PD, which examined 76 CAS that if effectively deployed between 2020 and 2050 would result in a cumulative reduction of 1051.01 gigatons (Gt) of CO_{2e} against the RES. Without formally correlating with Shared Socioeconomic Pathway (SSP) enhanced policy narratives *(18)*, Representative Concentration Pathways (RCP) 2.6 *(19)*, or the "well below 2°C above pre-industrial levels" goal of the Paris Agreement *(1)*, the PD Plausible scenario is roughly in line with these efforts to frame the scale and timeframe of responding to climate change *(15)*. Four categories were combined: on and offshore wind turbines, LED lighting household and commercial, improved rice cultivation and system of rice intensification, and large and small methane digesters, for a combined total of 72 CAS for our analysis.

The assumptions behind the plausible scenario were published in the first edition of the book, published in the spring of 2017 and additional references, technical details and updates of each CAS are available on the www.drawdown.org website. Since the primary focus of this inquiry is to explore the potential for using the Powers of 10 (P10) framework as it may relate to the optimization of implementation and scaling of CAS, all the assumptions used in the original PD analysis have been accepted for the purposes of this study. Like all the data used in this analysis, these assumptions will inevitably be revised, perhaps significantly, as new insights and data are incorporated, meaning the estimates of greenhouse gas reductions, costs and savings used provide a working scenario that will need to be updated as new information is available. For example, the assumption for concentrated solar power (CSP) is that this approach for generating renewable energy will grow from a current 0.04 percent of world electricity generation in 2014 to 4.3 percent of world electricity generation by 2050, which would help avoid 10.9 Gt of CO_{2e} emissions. While CSP implementation costs are high at USD 1.3 trillion and the Plausible scenario projects net savings of USD 414 billion, one of the strengths of CSP is that it can continue to produce and store energy after sunset, thereby helping stabilize grid operations during peak use periods. In the more ambitious "Drawdown" scenario, which envisions wider deployment of CSP, the estimated reduction of greenhouse gases is estimated at 26.01 Gt. As another example, the assumption for the Peatlands analysis was that 67% of currently intact peatlands would be protected, thereby protecting a stock of 336 Gt of carbon that would equate to roughly 1230 Gt of CO_{2e} if released into the atmosphere.

ANALYSIS OF THE POTENTIALITY OF P10

Recognizing the lack of precision and the wide variation of sizes of conventional frames of human population scales, such as “village,” “communities,” “cities”, “urban areas” and especially “nations” and “states”, we first examined the potential for using a logarithmic frame to explore the ten orders of magnitude between a single individual and 10 billion people as they relate to optimizing the deployment of sustainable practices. Using census data of the size of sovereign states and Zhao et al. (2017) (see enclosed Table S1 for details and the reference), we calculate the average and median sizes of the 194 sovereign nations and 40 metropolitan areas in 2017.

We note that more than half the signatory countries of the Paris Agreement have populations of 10 million people or less, yet there are roughly 40 megacities of 10 million people or more each (Table S1). Since there is no generally accepted definition of precisely what constitutes a megacity boundary and these cities are growing exponentially, delineating their growing size is difficult. The average size of the nations is approximately 39 million, e.g. the size of Iraq or Poland. The median is even less, i.e. around 9 million, e.g. the size of Switzerland or Honduras. In fact, over 100 nations (more than half) involved with the United Nations Framework Convention on Climate Change (UNFCCC) process are 10 million people or fewer. Thus, the 40 metropolitan areas with over 10 million inhabitants around the world have more than double the population of the bottom half of nations in the world. The combined total of the megacities’ population is more than double the total of the bottom half of the sovereign nations, which currently total 280 million people. Thus, we find comparing nations or cities that may vary in size several orders of magnitude is inherently problematic and imprecise. Many large cities, in fact, organize themselves in much small, more manageable sub-communities, which in turn may have even smaller neighborhood or community boards, as of course do ministries and departments of education, which ultimately are aimed at serving individuals.

We propose the “Powers of 10 (P10)” framework as a lens to examine with a greater degree of precision how segments of society relate to and can be engaged with and take meaningful action of local to global scale challenges, such as climate and other global sustainability changes (Fig. 1). Acknowledging that different population segments will benefit from and/or be able to support different strategies depending on their distinct situations, we use this logarithmic framework to inquire into current and future deployment of CAS and related sustainable practices in terms of the initial critical mass of people needed to begin effective implementation and the likely range of expansion in coming decades.

IDENTIFICATION OF OPTIMAL P10 COHORT RANGE

In this initial testing of the P10 framework, we examined the most likely societal scales for implementation and benefits for the CAS reviewed and modeled by the Plausible scenario in PD.

Estimating the range in the number of people or density of population who would be a "critical mass" to form agency for each strategy, we identified the P10 cohort and cohort ranges optimal for implementation of each of the 72 CAS. An iterative process of tagging and reviewing each CAS was conducted to estimate the range of population scale, where the strategy can be best deployed and implemented, using the exponential framework from the individual (P0) to the global (P10) scales.

We used the following criteria for appropriate cohorts or cohort range identification *(40)*:

- The number of people within the selected cohort or cohort range has the capability to form agencies for decision making to implement the particular CAS at hand;
- The number of people within the selected cohort or cohort range will actively engage and implement the CAS in question first hand through the formed agency; and
- The number of people within the selected cohort or cohort range and the formed agency will benefit or lose first hand economically from implementation of the CAS in questions.

Our concept of "agency for CAS implementation" includes individual, proxy and collective agencies *(43)*. Individual agency refers to situations, in which people bring their influence to bear their own functioning. Proxy, or socially mediated agency, refers to situations in which individuals have no direct control over conditions that affect their lives but they influence others who have the resources, knowledge, and means to act on their behalf to secure the outcome they desire. Collective agency refers to situations, in which individuals pool their knowledge, skills, and resources, and act in concert to shape their future *(43)*. We note that agencies other than nation states have been often overlooked in the existing international efforts such as Paris Agreement and Sustainable Development Goals (SDG), but that efforts such as the UNFCCC Non-State Actor Zone for Climate Action (NAZCA), as well as corporate and education efforts to support SDGs demonstrate increasing momentum for sub-national efforts *(44)*. We identified the individual, proxy and collective agencies that are optimal for deploying and implementing 72 CAS from individual to global scales that with the Plausible scenario will lead to 1051 Gt reduction of CO_{2e} between 2030 and 2050 against the RES.

Indeed, the implementation of a CAS requires policy and infrastructure support from multiple (and sometimes all) P10 cohorts, although the first-hand implementation will take place in a limited range of cohorts, where people have the most to gain or lose. Thus, top-down, large scale policies and support are important and individual decision-making and agency is critical, but the aim of this analysis was specifically to examine the relative agency of people who can best implement, benefit from and help scale-up these wide-ranging efforts. For example, household recycling or the use of clean cookstoves, are explicitly designed for small-scale implementation, e.g. individual (P0) to personal networks (P2), but both may require supporting infrastructure that could stretch around the world (P10) and involve thousands (P3 - P5) of other people. In other cases, such as protecting peatlands, wetlands and forests, or refrigerant management, there may be multiple scales, some ultra-local but with clear international dimensions for support. For energy, particularly generation of electricity, a "utility-scale" would be the most likely fit, but utilities vary in size and the number of customers, and related policy decisions may be made at a range of scales as well. Consequently, only the P10 cohorts, where people will actively form agencies, implement and directly benefit from the implementation of a CAS were chosen as the suitable cohorts for that CAS.

The iteration and identification of optimal P10 cohorts for implementing each of the CAS followed a three-step procedure:

1. The authors independently established an initial set of optimal P10 cohort or cohort ranges for deploying and implementing each of the CAS through individual, proxy and/or collective agencies based on reviewing related literature, real world examples and their own professional expertise.
2. The PD team member recommended P10 cohort ranges that were in line with the assumptions of agency on their analysis. Each of the authors independently suggested alternative set of P10 cohort ranges if they disagreed with the PD suggested cohorts.
3. The individual author cohort suggestions were combined with the PD recommendations to arrive at the final set (intersection set) of P10 cohorts with the highest authors-PD agreement, which were regarded as a robust and the most suitable set of cohorts for the implementation of each CAS.

The final set of P10 cohorts was further revised and evaluated through discussions among authors as well as with external experts.

CALCULATION OF CO_{2e} REDUCATION AND FINANCIAL BENEFIT

We calculated the total CO2e reduction, cost and savings for each P10 cohort as well as for the geographic scales and transformation spheres (20-21). First, the Project Drawdown assigned CO_{2e} reduction, cost and savings for each CAS against the RES that were weighted across the P10 cohorts according to their corresponding span following equations (i) and (ii).

$$\boldsymbol{a_i = A_i . w_i} \qquad , \qquad \boldsymbol{a, A, w \in R} \qquad \text{(i)}$$

$$\boldsymbol{f(r,c,s)_i = f(R,C,S)_i . \frac{(p+1)_i}{\sum_{i=1}^{n}(p+1}} \qquad , \qquad \boldsymbol{r, R, c, C, s, S \in R, p = 0 - 10} \qquad \text{(ii)}$$

$\boldsymbol{A}$ is the function of the CO_{2e} reduction ($\boldsymbol{R}$), cost ($\boldsymbol{C}$) and savings ($\boldsymbol{S}$) assigned to a CAS by PD, each of which was weighted ($\boldsymbol{r, c, s}$ indicate weighted CO_{2e} reduction, cost and savings, respectively) by a weighting variable $\boldsymbol{w}$. The value of $\boldsymbol{w}$ for a CAS ($\boldsymbol{i}$th) was obtained for each of the P10 cohort by dividing the power of that cohort ($\boldsymbol{p_i}$, 1 was added to avoid 0 weight for the individual cohort (P0)) by the sum of the powers of the P10 cohort ranges ($\boldsymbol{\sum_{i=1}^{n}(p+1)}$), across which that CAS can be optimally implemented. For example, the PD assigned CO_{2e} reduction from "educating girls" CAS is 59.60 Gt and the optimal cohort for implementing this CAS spans from the individual (P0) to the community (P4) cohorts. Hence, the reduction of CO_{2e} at the individual cohort through the implementation of "educating girls" CAS is = 59.60 * (0+1)/((0+1)+(1+1)+(2+1)+(3+1)+(4+1)) = 3.78 Gt. Thus, a larger P10 cohort entailed a larger impact by implementing a CAS, and vice-versa (Fig.1).

The weighted CO_{2e} reduction, cost and savings for all CAS that can be optimally implemented in a P10 cohort were sum aggregated to arrive at the total CO_{2e} reduction, cost and savings from climate action in that P10 cohort. The total cost in a P10 cohort was deducted from the total savings to calculate the total financial benefit from climate action (negative values indicated loss). Note that for 21 CAS, benefit value could not be calculated (NA values in Table 2) as either cost or savings data were missing (NA) in the Project Drawdown data since they either could not be modeled because of their high geographic and sectoral variability or have already been calculated in other solutions. The total CO_{2e} reduction and benefit for a geographic scale and transformation sphere were the sum aggregates of the CO_{2e} reductions and benefits of the constituting P10 cohorts in that geographic scale and transformation sphere, respectively (Fig. 3).

SWEET SPOT FOR CAS IMPACT OPTIMIZATION

Since the range of the number of people who may be involved and benefit from a particular strategy may be large, we calculated the median of the range (a cohort that separates the lower half of the range from the upper half) as an indicator of the "sweet spot". Note that as we assumed a larger P10 cohort entailed a larger impact by implementing a CAS, and vice-versa, but we regarded the median cohort (mid-point) as the sweet spot from where the CAS impact can be maximally disseminated and cascaded downwards and upwards, respectively.

The medians of the ranges for all CAS in a sector and the total 72 CAS were calculated as the sectoral and overall sweet spots for maximizing climate action impact. In addition, we ranked the P10 cohorts according to their aggregate CO_{2e} reduction and benefit and identified the cohorts with the highest aggregate CO_{2e} reduction and benefit to validate the sweet spot ranges and results.

Supplementary Text

An Example Case of Optimizing Climate Action at the Sweet Spot

Thurston County, Washington State, USA, and its sub-communities offers an example case of how climate action is being maximized in the sweet spot cohort range of community to urban scales, referred to in the P10 framework as P4 - P6, or 10,000 to 1,000,000 people (Fig. S1). This sweet spot is where, according to our research using data from the Plausible scenario of PD, nearly two-thirds (64%) of climate action strategies and maximizing net CO_{2e} reduction can be achieved, providing there is also strong amplification of individual, household and neighborhood efforts (P0 - P3), incubation of climate action solutions (CAS) starting at the village and community scales (P3 - P4), and alignment with larger scale solutions and policies (P7 - P10) (Fig. 2).While Thurston County has not deliberately used the P10 framework or conducted an analysis of which PD CAS are most appropriate for the region and its population, we present this as a real-world example of how climate action at the sweet spot can potentially be catalyzed to support top-down and bottom-up engagement to reduce climate risks and increase social and environmental resilience.

Thurston County is home to the Washington State capitol, Olympia (population 54,000), two contiguous communities of Lacey (50,000) and Tumwater (24,000) and outer lying smaller towns and rural areas for a county-wide population of 270,000 (P5) (Fig. S1). The county sits on the southern end of Puget Sound in a bustling bioregion of over 4.5 million known for its high-tech, bio-tech, aerospace, food, retail, travel and recreation innovations and opportunities. Puget Sound, Washington State and U.S. Northwest are in the P7 scale, which are located on the West Coast of North America (P8), and North and South America (P9). Because Thurston County is the seat of the state capital, it's economy and culture are primarily based on Washington State government, but it also involves agriculture, tree farming, shellfish aquaculture, and has three colleges, nine school districts, and wide-ranging additional public and private enterprises and services that employ and support the population. The county is expected to grow over 40% by 2040 to 400,000 people.

Sea-level rise, increased precipitation in the winter and drought in the summer leading to more frequent floods, tidal surges fires, high-wind storms, landslides, ocean acidification, public health hazards and damaged property, along with the risks of threatened food supplies and health epidemics have become Thurston County's "new normal". In 2015, the City of Olympia joined over 7500 cities in the Global Covenant of Mayors agreeing to assess carbon generation, set greenhouse gas reduction targets, and develop and implement climate action and resilience plans. The Thurston County Regional Planning Council (TRPC), comprised of elected and appointed officials from jurisdictions, businesses, tribes and community organizations is the coordinating entity for Thurston County's response to climate change. As a first step, TRPC completed energy and carbon assessments and mapped the sources and end use of carbon emissions.

Underscoring their intent to achieve the "best-case" scenario above, the cities of Olympia, Lacey and Tumwater and Thurston County policy leaders negotiated in 2018 to combine resources and jointly commit to an 80% below the 2015 baseline greenhouse gas emission reduction by 2050 (Fig. S2). Beginning in 2018-2019, they will engage the community to inform and take significant, coordinated actions. Additionally, since Olympia's downtown sits only a few feet above high tide, on landfill, the city is working with the Port of Olympia and the regional wastewater treatment utility, to plan for subsidence, sea-level rise and increased flooding. And, in January 2018, TRPC approved the Thurston Climate Adaptation Plan to help residents, businesses and others to reduce risks, respond to impacts, and remain resilient in the face of climate destabilization.

While a full analysis of potential PD CAS in Thurston County has not yet been conducted, many are currently being deployed and have potential to be expanded upon. Environmental stewardship is long an integral part of the region modeled by the Steh-Chas and other bands of the Nisqually Nation, the Squaxin Nation and other Salish tribes, and underscores efforts among all decision-makers at the state and local levels to reduce climate change risks. A Carbon Wedge Analysis is another tool TRPC completed showing local, state and federal policy "wedges" of emissions saved over time. The existing state and federal policies alone will not achieve the GHG reductions needed (Fig. S3). However, the solid sections, including action from the state utilities commission, Governor and legislature are elemental to Thurston County meeting its targets in coming years (Fig. S3).

Thurston County at the P5 scale is in a sweet spot for PD solutions. Many such as Plant Rich Diet, Reducing Food Waste and Rooftop Solar are ideally suited to the area given its land, economic and social service resources. A baseline inventory of existing and potential solutions could be developed with the help of local schools, colleges, businesses, municipalities and neighborhoods. The area's citizen climate action umbrella organization, Thurston Climate Action Team holds an annual Climate Convention. In 2018, local initiatives addressing the top 10 PD solutions were featured. Additionally, a Thurston Climate Reality Speakers Bureau, launched in early 2018, provides high quality, up-to-date, locally contextualized presentations and workshops to inform, connect and inspire action in individuals and groups. An early indicator of their success was when the Bureau, along with Thurston Climate Action Team and the Thurston Thrives public health consortium, helped a skeptical Thurston County Commission see recognize local impacts of climate disruption and unanimously vote to support the climate action planning. As Eileen V. Quigley, Director, Clean Energy Transition an energy expert who guided Thurston Counties energy assessment efforts stated,

> *"Smaller cities can sometimes make more progress than larger ones because there tends to be first-name basis connections among elected officials, community leaders, and citizens, and oftentimes there can be less bureaucracy. However, cities reducing emissions one-off is not enough, so banding together contiguous communities, who are all seeking to reduce their emissions on the same scale and timeline, in counties or in utility district territories is a critical strategy. However, local action is not a substitute for statewide policies; both are needed and ideally are integrated."*

With Olympia as the seat of state government, local leaders are also positioned to influence policy impacting all Washington State communities. For example, in March 2018, the legislature approved a nationally historic level of 4 million USD for climate science literacy in schools state-wide. The effort to secure this funding had a strong local element given that those who work in the Governor's office and legislature, and in state and local government agencies and civic, business, tribal, educational and other citizen organizations, generally live in or around Thurston County. Given the diversity of opinion and perspective within the county face-to-face dialogue, cultural responsiveness, effective education and outreach, and physical spaces that make information accessible and inspire action through example are critical, ideally at the P2 - P4 scales. These practices tailored to the needs of humans, other living beings and visitors of the community can optimize climate policies, actions and funding at the rate and scale required to sustain life and humanely transition to a clean energy economy and society. According to Nathaniel Jones, Chair Thurston Regional Planning Council and Mayor Pro-Tem, City of Olympia,

> *"State and local policy development systems, operating per their 18th-19th century founding, are congenitally predisposed to minimize risk and uncertainty. Change-agents,*

> *who grasp the urgency of climate disruption, need workable strategies to authentically inspire new, clean energy results. Locally contextualizing Drawdown solutions and effectively utilizing current information and media systems will help us redefine our identity as a clean-energy region, which has embraced the new energy economy."*

Overall, the P10 framework has the potential to help decision-makers, business leaders, citizens and students of Thurston County and similar communities to:

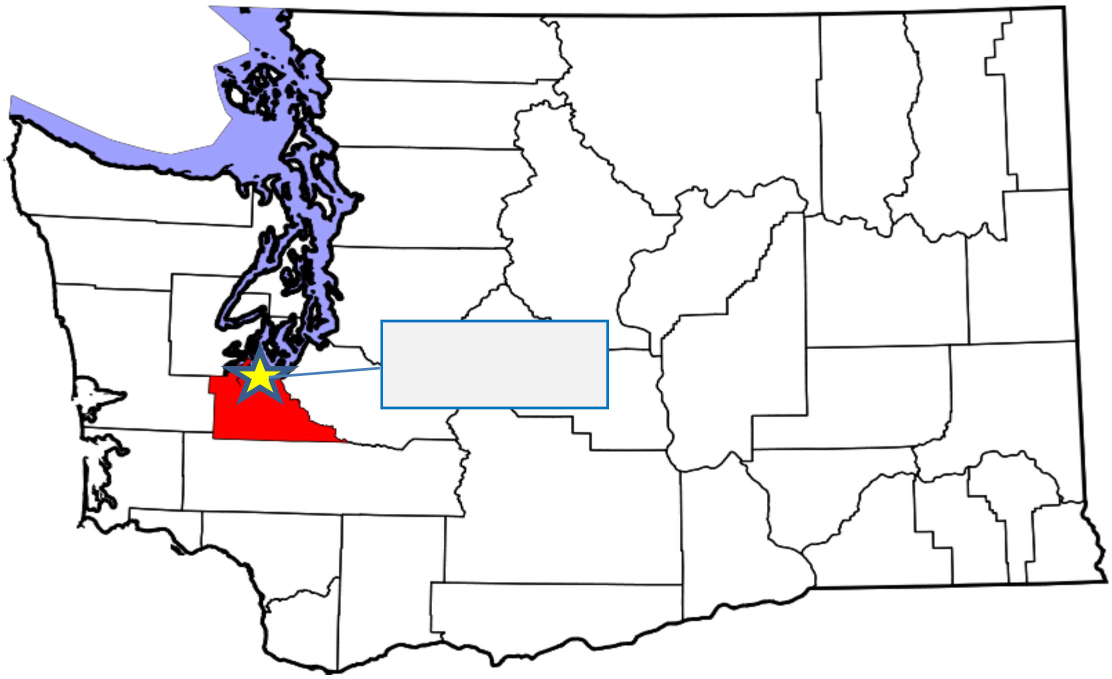
- Recognize their connections to larger scales (P6 - P10);

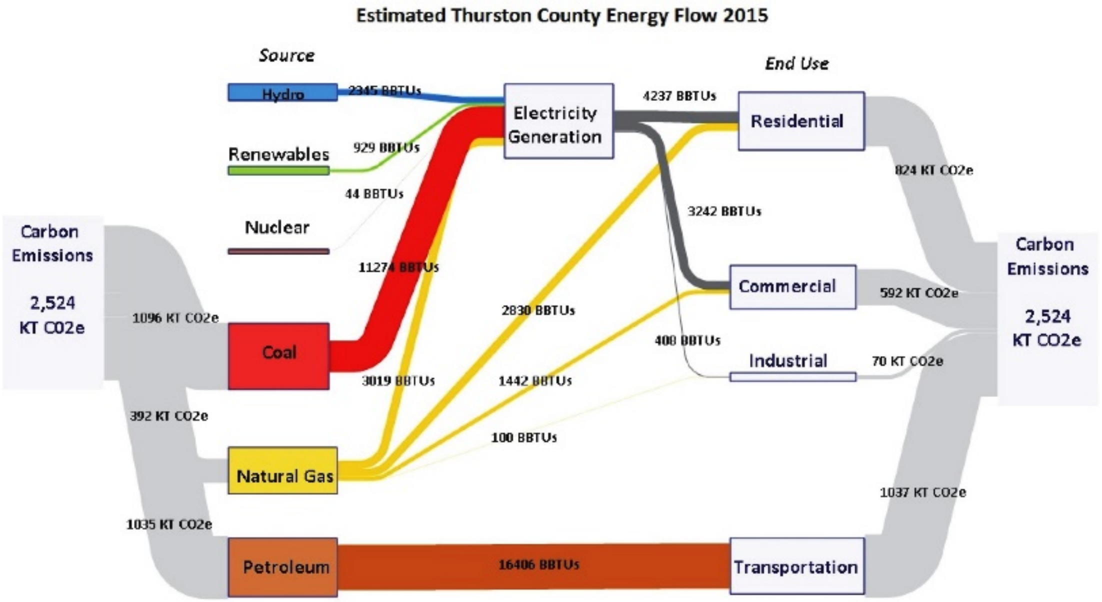
- Assist in the development of narratives and the targeting, customization and evaluation of specific interventions; and

- Enhance the methodical identification of barriers and opportunities at the scales (P0 - P5), where they have individual and collective agency over.

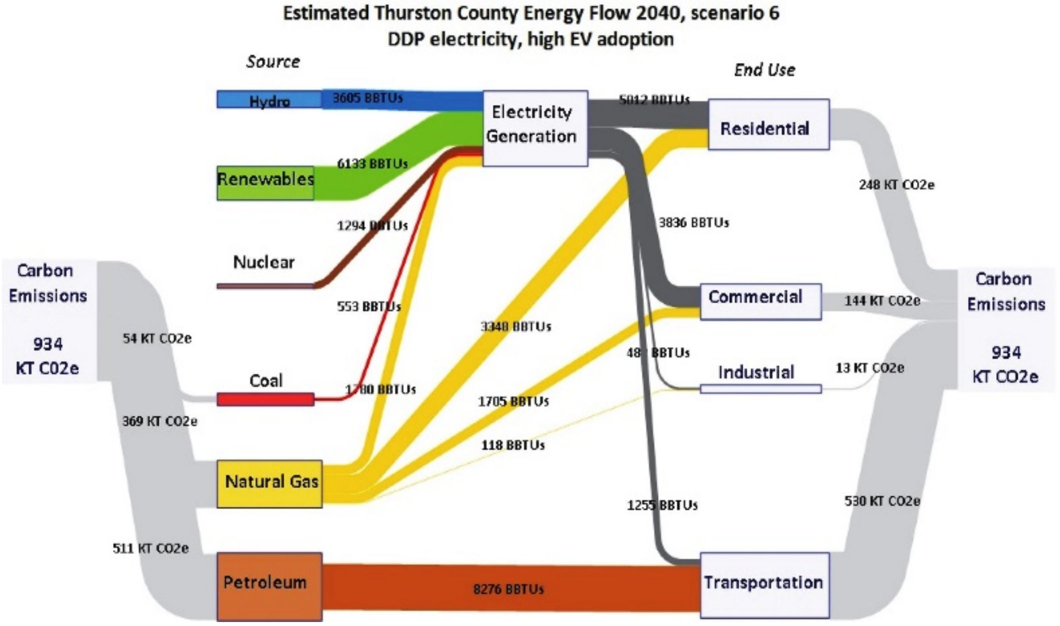
Future research is currently being planned to investigate whether and how the framework and related CAS analysis can be applied in this communities and other sweet spots around the world.

Supplementary Figures

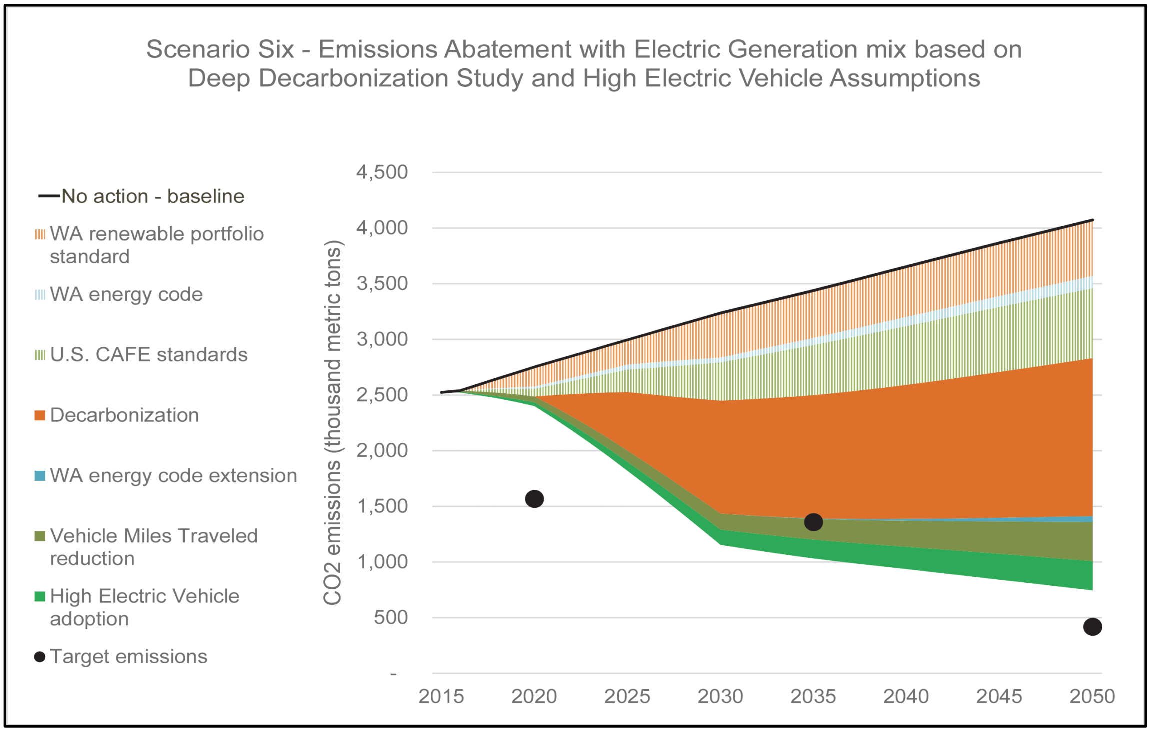




Estimated Thurston County Energy Flow 2015



Estimated Thurston County Energy Flow 2040, scenario 6
DDP electricity, high EV adoption



Scenario Six - Emissions Abatement with Electric Generation mix based on Deep Decarbonization Study and High Electric Vehicle Assumptions

Supplementary Tables

Table S1: Populations of the (a) nations and (b) major metropolitans of the world.

(a)

United Nations Signatory ID	Nation Name	Total Population	Estimation or Census Date	Percentage Coverage of Global Population	Link to the Source
1	China	1 387 060 000	October 22, 2017	18.30%	2016 China Statistical Yearbook
2	India	1 322 890 000	October 22, 2017	17.50%	Official population clock
3	United States	325 975 000	October 22, 2017	4.30%	Official population clock
4	Indonesia	261 890 900	July 1, 2017	3.46%	Official annual projection
5	Pakistan	209 321 000	October 22, 2017	2.76%	Pakistan Bureau of Statistics
6	Brazil	208 159 000	October 22, 2017	2.75%	Official population clock
7	Nigeria	193 500 543	July 1, 2016	2.55%	Official annual projection
8	Bangladesh	163 348 000	October 22, 2017	2.16%	Official population clock
9	Russia	146 809 643	August 1, 2017	1.94%	Official estimate
10	Japan	126 670 000	September 1, 2017	1.67%	Monthly provisional estimate
11	Mexico	123 364 426	July 1, 2017	1.62%	Official projection
12	Philippines	104 774 000	October 22, 2017	1.38%	Official population clock
13	Egypt	95 900 800	October 22, 2017	1.27%	Official population clock
14	Ethiopia	94 352 000	July 1, 2017	1.25%	Official Projection
15	Vietnam	93 700 000	July 1, 2017	1.24%	Annual official projection
16	Germany	82 800 000	December 31, 2016	1.09%	Provisional official annual estimate
17	Democratic Republic of the Congo	81 339 988	July 1, 2017	1.09%	UN Projection
18	Iran	80 523 100	October 22, 2017	1.06%	Official population clock
19	Turkey	79 814 871	December 31, 2016	1.05%	Annual official estimate
20	Thailand	69 037 513	July 1, 2017	0.91%	UN Projection
21	France	67 135 000	September 1, 2017	0.89%	Monthly official estimate
22	United Kingdom	65 648 000	July 1, 2016	0.87%	Official mid-year estimate
23	Italy	60 518 005	May 31, 2017	0.80%	Official estimate
24	Tanzania[Note 7]	57 310 000	July 1, 2017	0.76%	UN projection
25	South Africa	56 521 900	July 1, 2017	0.75%	Annual official estimate
26	Myanmar	53 370 609	July 1, 2017	0.70%	UN projection
27	South Korea	51 446 201	July 1, 2017	0.68%	Annual official estimate
28	Kenya	49 699 862	July 1, 2017	0.66%	UN projection
29	Colombia	49 459 500	October 22, 2017	0.65%	Official population clock
30	Spain	46 528 966	January 1, 2017	0.61%	Official estimate
31	Argentina	44 044 811	July 1, 2017	0.58%	Official annual projection

32	Ukraine	42 456 012	August 1, 2017	0.56%	Monthly official estimate
33	Algeria	41 697 498	July 1, 2017	0.55%	Official annual projection
34	Sudan	40 782 742	July 1, 2017	0.54%	Official annual projection
35	Poland	38 432 992	December 31, 2016	0.51%	Official estimate
36	Iraq	38 274 618	July 1, 2017	0.49%	UN projection
37	Uganda	37 673 800	July 1, 2017	0.50%	Official annual projection
38	Canada	36 695 100	October 22, 2017	0.48%	Official estimate
39	Morocco	34 469 800	October 22, 2017	0.46%	Official annual projection
40	Saudi Arabia	34 135 000	July 1, 2017	0.45%	Official estimate
41	Uzbekistan	32 345 000	July 1, 2017	0.42%	Official population report
42	Malaysia	32 260 700	October 22, 2017	0.43%	Official population clock
43	Peru	31 826 018	July 1, 2017	0.42%	Official annual projection
44	Venezuela	31 431 164	July 1, 2017	0.41%	Official annual projection
45	Afghanistan	29 724 323	July 1, 2017	0.39%	Annual official estimate
46	Ghana	28 956 587	July 1, 2017	0.38%	Official annual projection
47	Nepal	28 825 709	July 1, 2017	0.38%	Official annual projection
48	Angola	28 359 634	January 1, 2017	0.37%	Official Estimate
49	Yemen	28 250 000	July 1, 2017	0.37%	UN projection
50	Mozambique	27 128 530	July 1, 2017	0.36%	Annual official projection
51	Madagascar	25 571 000	July 1, 2017	0.34%	UN projection
52	North Korea	25 491 000	July 1, 2017	0.34%	UN projection
53	Australia	24 691 500	October 22, 2017	0.33%	Official population clock
54	Ivory Coast	24 295 000	July 1, 2017	0.32%	UN projection
55	Taiwan	23 557 467	September 31, 2017	0.31%	Monthly official estimate
56	Cameroon	23 248 044	January 1, 2017	0.31%	Annual official projection
57	Niger	21 477 348	July 1, 2017	0.28%	UN projection
58	Sri Lanka	21 203 000	July 1, 2016	0.28%	Official estimate
59	Romania	19 638 000	January 1, 2017	0.26%	Annual official estimate
60	Burkina Faso	19 632 147	July 1, 2017	0.26%	Annual official projection
61	Malawi	18 622 000	July 1, 2017	0.25%	UN Projection
62	Mali	18 542 000	July 1, 2017	0.24%	UN projection
63	Syria	18 270 000	July 1, 2017	0.24%	UN projection
64	Kazakhstan	18 074 100	September 1, 2017	0.24%	Official estimate
65	Chile	17 373 831	August 31, 2017	0.24%	Preliminary 2017 Census Results
66	Netherlands	17 165 100	October 22, 2017	0.23%	Official population clock
67	Ecuador	16 836 200	October 22, 2017	0.22%	Official population clock
68	Zambia	16 405 229	July 1, 2017	0.22%	Official annual projection
69	Guatemala	16 176 133	July 1, 2015	0.21%	Official estimate
70	Cambodia	15 848 495	July 1, 2017	0.21%	Official annual projection

71	Senegal	15 256 346	January 1, 2017	0.20%	Official annual projection
72	Chad	14 900 000	July 1, 2017	0.20%	UN projection
73	Somalia	14 743 000	July 1, 2017	0.19%	UN projection
74	Zimbabwe	14 542 235	July 1, 2017	0.19%	Official annual projection
75	Guinea	12 717 176	July 1, 2017	0.17%	UN projection
76	South Sudan	12 575 714	July 1, 2017	0.17%	UN projection
77	Rwanda	11 809 300	July 1, 2017	0.16%	Official projection (medium scenario)
78	Belgium	11 370 968	August 1, 2017	0.15%	Monthly official estimate
79	Tunisia	11 304 482	July 1, 2016	0.15%	Official estimate
80	Cuba	11 239 224	December 31, 2016	0.15%	Annual official estimate
81	Greece	11 183 716	January 1, 2016	0.14%	Official estimate
82	Bolivia	11 145 770	July 1, 2017	0.15%	Official Estimate
83	Benin	11 002 578	July 1, 2017	0.15%	Official projection
84	Haiti	10 911 819	March 31, 2015	0.14%	Official estimate
85	Czech Republic	10 588 063	June 30, 2017	0.14%	Official quarterly estimate
86	Burundi	10 400 938	July 1, 2017	0.14%	Official annual projection
87	Portugal	10 309 573	December 31, 2016	0.14%	Annual official estimate
88	Dominican Republic	10 169 172	July 1, 2017	0.13%	Official projection
89	Sweden	10 081 396	August 31, 2017	0.13%	Official monthly estimate
90	Jordan	9 995 600	October 22, 2017	0.13%	Official population clock
91	Azerbaijan	9 867 250	September 1, 2017	0.13%	Official estimate
92	Hungary	9 799 000	January 1, 2017	0.13%	Annual official estimate
93	Belarus	9 495 500	July 1, 2017	0.13%	Official quarterly estimate
94	United Arab Emirates	9 400 000	July 1, 2017	0.12%	UN projection
95	Honduras	8 866 351	July 1, 2017	0.12%	Official annual projection
96	Austria	8 794 267	July 1, 2017	0.12%	Quarterly provisional figure
97	Israel	8 760 920	October 22, 2017	0.12%	Official population clock
98	Tajikistan	8 829 300	July 1, 2017	0.12%	Official estimate
99	Switzerland	8 448 585	June 30, 2017	0.11%	Quarterly provisional figure
100	Papua New Guinea	8 151 300	July 1, 2016	0.11%	Annual official estimate
–	Hong Kong (China)	7 389 500	July 1, 2017	0.10%	Official estimate
101	Togo	7 178 000	July 1, 2017	0.10%	Official estimate
102	Bulgaria	7 101 859	December 31, 2016	0.09%	Official estimate
103	Sierra Leone	7 075 641	December 4, 2015	0.09%	Preliminary 2015 census result
104	Serbia	7 058 322	June 30, 2016	0.09%	Annual official estimate
105	Paraguay	6 953 646	January 1, 2017	0.09%	Official estimate
106	El Salvador	6 581 940	July 1, 2017	0.09%	Official projection
107	Laos	6 492 400	March 1, 2015	0.09%	Preliminary 2015 census result
108	Libya	6 374 616	July 1, 2017	0.08%	UN projection

109	Nicaragua	6 305 956	July 1, 2017	0.08%	Official estimate
110	Kyrgyzstan	6 140 200	January 1, 2017	0.08%	Official estimate
111	Lebanon	6 082 000	July 1, 2017	0.08%	UN projection
112	Denmark	5 760 694	July 1, 2017	0.08%	Official quarterly estimate
113	Turkmenistan	5 758 000	July 1, 2017	0.08%	UN projection
114	Singapore	5 612 300	July 1, 2017	0.07%	Official estimate
115	Finland	5 508 714	July 31, 2017	0.07%	Monthly official estimate
116	Slovakia	5 435 343	December 31, 2016	0.07%	Official estimate
117	Norway	5 277 762	July 1, 2017	0.07%	Official quarterly estimate
118	Republic of the Congo	5 261 000	July 1, 2017	0.07%	UN projection
119	Central African Republic	4 659 080	July 1, 2017	0.06%	UN projection
120	Eritrea	5 069 000	July 1, 2017	0.07%	UN projection
121	Costa Rica	4 947 490	June 30, 2017	0.07%	Official estimate
122	New Zealand	4 827 550	October 22, 2017	0.06%	Official population clock
–	Palestine	4 816 503	July 1, 2016	0.06%	Official estimate
123	Ireland	4 757 976	July 14, 2016	0.06%	Preliminary 2016 census result
124	Oman	4 573 075	February 1, 2017	0.06%	Official estimate
125	Liberia	4 289 520	July 1, 2017	0.06%	Official projection[Note 13]
126	Croatia	4 154 213	December 31, 2016	0.06%	Annual official estimate
127	Kuwait	4 132 415	July 1, 2016	0.06%	Official estimate
128	Panama	4 037 043	July 1, 2016	0.05%	Official estimate
129	Mauritania	3 806 719	July 1, 2017	0.05%	Annual official projection
130	Georgia	3 718 200	January 1, 2017	0.05%	Annual official estimate
131	Moldova	3 550 900	January 1, 2017	0.05%	Official estimate
132	Bosnia and Herzegovina	3 518 000	July 1, 2015	0.05%	Official estimate
133	Uruguay	3 493 205	June 30, 2017	0.05%	Annual official projection
–	Puerto Rico (U.S.)	3 411 307	July 1, 2016	0.05%	Official estimate
134	Mongolia	3 175 350	October 22, 2017	0.04%	Official population clock
135	Armenia	2 979 900	July 1, 2017	0.04%	Official quarterly estimate
136	Albania	2 876 591	January 1, 2017	0.04%	Annual official estimate
137	Lithuania	2 814 696	October 1, 2017	0.04%	Monthly official estimate
138	Jamaica	2 730 894	December 31, 2016	0.04%	Official estimate
139	Qatar	2 675 522	January 31, 2017	0.04%	Monthly official estimate
140	Namibia	2 368 747	July 1, 2017	0.03%	Official projection
141	Botswana	2 230 905	July 1, 2016	0.03%	Official annual projection
142	Lesotho	2 233 000	July 1, 2017	0.03%	UN projection
143	The Gambia	2 101 000	July 1, 2017	0.03%	UN projection
144	Macedonia	2 073 702	December 31, 2016	0.03%	Official estimate
145	Slovenia	2 065 895	January 1, 2017	0.03%	Official estimate

146	Latvia	1 933 200	October 1, 2017	0.03%	Monthly official estimate
–	Kosovo	1 836 978	January 1, 2016	0.02%	Official annual projection
147	Gabon	1 811 079	June 2, 2016	0.02%	Estimate (press release)
148	Guinea-Bissau	1 553 822	July 1, 2017	0.02%	Official annual projection
149	Bahrain	1 451 200	July 1, 2017	0.02%	Official annual projection
150	Trinidad and Tobago	1 353 895	July 1, 2016	0.02%	Official estimate
151	Estonia	1 352 320	January 1, 2017	0.02%	Official estimate
152	Mauritius	1 263 820	December 31, 2016	0.02%	Official estimate
153	Equatorial Guinea	1 222 442	July 4, 2015	0.02%	Preliminary 2015 census result
154	East Timor	1 167 242	July 11, 2015	0.02%	Preliminary 2015 census result
155	Swaziland	1 132 657	July 1, 2016	0.02%	Official projection
156	Djibouti	956 985	July 1, 2017	0.01%	UN projection
157	Fiji	869 458	July 1, 2015	0.01%	Annual official estimate
158	Cyprus	848 300	December 31, 2015	0.01%	Official estimate
159	Comoros	806 153	July 1, 2016	0.01%	Official estimate
160	Bhutan	792 540	October 22, 2017	0.01%	Official population clock
161	Guyana	746 900	July 1, 2013	0.01%	Official estimate
–	Macau (China)	648 300	March 31, 2017	0.01%	Official quarterly estimate
162	Solomon Islands	642 000	July 1, 2015	0.01%	Annual official estimate
163	Montenegro	622 387	January 1, 2017	0.01%	Official estimate
164	Luxembourg	590 667	January 1, 2017	0.01%	Official estimate
–	Western Sahara	552 628	July 1, 2017	0.01%	UN projection
165	Suriname	541 638	August 13, 2012	0.01%	Final 2012 census result
166	Cape Verde	531 239	July 1, 2016	0.01%	Official annual projection
–	Transnistria	475 665	October 15, 2015	0.01%	Preliminary 2015 census result
167	Malta	429 344	December 31, 2014	0.01%	Official estimate
168	Brunei	417 200	July 1, 2015	0.01%	Official estimate
169	Belize	380 010	October 1, 2016	0.01%	Official estimate
170	Bahamas	378 040	July 1, 2016	0.01%	Official projection
171	Maldives	344 023	September 20, 2014	0.00%	Preliminary 2014 census result
172	Iceland	343 960	June 30, 2017	0.00%	Official quarterly estimate
–	Northern Cyprus	313 626	June 30, 2014	0.00%	Official estimate
173	Barbados	285 719	July 1, 2017	0.00%	UN projection
174	Vanuatu	277 500	July 1, 2015	0.00%	Annual official estimate
–	French Polynesia (France)	271 800	December 31, 2014	0.00%	Official estimate
–	New Caledonia (France)	268 767	August 26, 2014	0.00%	Preliminary 2014 census result
–	Abkhazia	240 705	February 28, 2011	0.00%	2011 census result
175	Samoa	196 315	January 1, 2017	0.00%	Official projection
176	São Tomé and Príncipe	187 356	May 13, 2012	0.00%	2012 census result

177	Saint Lucia	178 844	July 1, 2017	0.00%	UN projection
–	Guam (U.S.)	184 200	July 1, 2015	0.00%	Annual official estimate
–	Curaçao (Netherlands)	160 337	January 1, 2017	0.00%	Annual official estimate
–	Artsakh[	150 932	December 1, 2015	0.00%	Preliminary 2015 census result
178	Kiribati	113 400	July 1, 2015	0.00%	Annual official estimate
–	Aruba (Netherlands)	110 882	June 30, 2017	0.00%	Official quarterly estimate
179	Saint Vincent and the Grenadines	109 991	June 12, 2012	0.00%	Preliminary 2012 census result
–	United States Virgin Islands (U.S.)	104 901	July 1, 2017	0.00%	UN projection
–	Jersey (UK)	104 200	December 31, 2016	0.00%	Annual official estimate
180	Grenada	103 328	May 12, 2011	0.00%	2011 census result
181	Tonga	103 252	November 30, 2011	0.00%	2011 census result
182	Federated States of Micronesia	102 800	July 1, 2015	0.00%	Annual official estimate
183	Seychelles	94 205	December 31, 2016	0.00%	Official estimate
184	Antigua and Barbuda	86 295	May 27, 2011	0.00%	Preliminary 2011 census result
–	Isle of Man (UK)	83 314	April 24, 2016	0.00%	2016 census result
185	Andorra	78 264	December 31, 2016	0.00%	Annual official estimate
186	Dominica	71 293	May 14, 2011	0.00%	Preliminary 2011 census result
–	Guernsey (UK)	62 723	March 31, 2016	0.00%	Official estimate
–	Bermuda (UK)	61 954	July 1, 2013	0.00%	Official estimate
–	Cayman Islands (UK)	60 413	December 31, 2015	0.00%	Official estimate
–	American Samoa (U.S.)	57 100	July 1, 2015	0.00%	Annual official estimate
–	Northern Mariana Islands (U.S.)	56 940	July 1, 2015	0.00%	Annual official estimate
–	Greenland (Denmark)	56 483	September 14, 2016	0.00%	Annual official estimate
187	Marshall Islands	54 880	July 1, 2015	0.00%	Annual official estimate
–	South Ossetia[Note 22]	53 532	October 15, 2015	0.00%	Preliminary 2015 census result
–	Faroe Islands (Denmark)	50 451	August 1, 2017	0.00%	Monthly official estimate
188	Saint Kitts and Nevis	46 204	May 15, 2011	0.00%	2011 census result
–	Sint Maarten (Netherlands)	39 410	January 1, 2016	0.00%	Official estimate
189	Liechtenstein	37 815	December 31, 2016	0.00%	Semi annual official estimate
190	Monaco	37 550	December 31, 2016	0.00%	Annual official estimate
–	Saint-Martin (France)	36 457	January 1, 2015	0.00%	Annual official estimate
191	San Marino	33 230	June 30, 2017	0.00%	Monthly official estimate
–	Gibraltar (UK)	33 140	December 31, 2014	0.00%	Annual official estimate
–	Turks and Caicos Islands (UK)	31 458	January 25, 2012	0.00%	2012 census result
–	British Virgin Islands (UK)	28 514	July 1, 2013	0.00%	Official estimate
–	Cook Islands (NZ)	18 100	March 1, 2016	0.00%	Official quarterly estimate
192	Palau	17 950	July 1, 2015	0.00%	Annual official estimate
–	Anguilla (UK)	13 452	May 11, 2011	0.00%	Preliminary 2011 census result
–	Wallis and Futuna (France)	11 750	July 1, 2015	0.00%	Annual official estimate

193	Tuvalu	10 640	November 4, 2012	0.00%	2012 census result
194	Nauru	10 084	October 30, 2011	0.00%	2011 census result
–	Saint Barthélemy (France)	9 417	January 1, 2015	0.00%	Annual official estimate
–	Saint Pierre and Miquelon (France)	6 286	January 1, 2015	0.00%	Annual official estimate
–	Saint Helena, Ascension and Tristan da Cunha (UK)	5 633	February 7, 2016	0.00%	2016 census result
–	Montserrat (UK)	4 922	May 12, 2011	0.00%	2011 census result
–	Falkland Islands (UK)	2 563	April 15, 2012	0.00%	2012 census result
–	Norfolk Island (Australia)	2 302	August 9, 2011	0.00%	2011 census result
–	Christmas Island (Australia)	2 072	August 9, 2011	0.00%	2011 census result
–	Niue (NZ)	1 470	July 1, 2015	0.00%	Annual official estimate
–	Tokelau (NZ)	1 411	October 18, 2011	0.00%	2011 census result
195	Vatican City	800	January 1, 2014	0.00%	Official estimate
–	Cocos (Keeling) Islands (Australia)	550	August 9, 2011	0.00%	2011 census result
–	Pitcairn Islands (UK)	57	July 1, 2014	0.00%	Official estimate
	Total	**7 479 788 324**			
	Average	**38 555 610**	**Poland/Iraq**		
	Median	**8.8M**	**Isreal/Tajikistan**		
	Bottom half	**279 801 507**			

(b)

Metropolitan Name	Nation	Population in Millions	Estimation or Census Date
Tokyo	Japan	37.8	2016
Shanghai	China	34	2010
São Paulo	Brazil	33.4	2016
Jakarta	Indonesia	31.7	2015
Delhi	India	26.4	2016
Seoul	South Korea	25.5	2016
Karachi	Pakistan	25.1	2016
Guangzhou	China	25	2010
Beijing	China	25	2010
Shenzhen	China	23.3	2010
Mexico City	Mexico	21.3	2015
Lagos	Nigeria	21	2014
Mumbai	India	20	2011
New York	United States	20.7	2016
Keihanshin (Kyoto-Osaka-Kobe)	Japan	19.3	2010
Moscow	Russia	19	2016
Wuhan	China	19	2010
Chengdu	China	18	2010
Dhaka	Bangladesh	17	2011
Chongqing	China	17	2010
Tianjin	China	15.4	2010
Istanbul	Turkey	14.8	2016
Kolkata	India	14.6	2011
Tehran	Iran	14.6	2011
London	United Kingdom	13.8	2015
Hangzhou	China	13.4	2010
Los Angeles	United States	13.3	2016
Buenos Aires	Argentina	13	2010
Xi'an	China	12.9	2010
Manila	Philippines	12.8	2015
Changzhou	China	12.4	2010
Rio de Janeiro	Brazil	12.3	2016
Paris	France	12.1	2015
Shantou	China	12	2010
Nanjing	China	11.7	2010

Rhine-Ruhr	Germany	11.4	2006
Jinan	China	11	2010
Chennai	India	11	2011
Harbin	China	10.5	2010
Lahore	Pakistan	10.5	201
	Total	**733**	
Source	Zhao, S. X., Guo, N. S., Li, C. L. K. & Smith, C. Megacities, the World's Largest Cities Unleashed: Major Trends and Dynamics in Contemporary Global Urban Development. World Development 98, 257–289 (2017).		
Note	There is currently no generally accepted, globally consistent definition of exactly what constitutes a metropolitan area, thus making comparisons between cities in different countries especially difficult. However, for consistency, the sources on this article include official figures from governments only.		