urban science and praxis. The topics raised here are a modest contribution to this end. Timing is an essential factor for strengthening CCA planning and its implementation in cities. The dynamics of urban growth in the Global South this century creates a limited timeframe to develop adaptation strategies at an affordable cost and to avoid lock-in, which would limit options in the future[22]. We are particularly concerned that insufficient responses for emerging climate change impacts are already eroding the basis for sustainable development. ❐

Roberto Sanchez Rodriguez[1]*, Diana Ürge-Vorsatz[2] and Aliyu Salisu Barau[3]
[1]*Department of Urban and Environmental Studies, El Colegio de la Frontera Norte, Tijuana, Mexico.*
[2]*Department of Environmental Sciences and Policy, Central European University, Budapest, Hungary.*
[3]*Department of Urban and Regional Planning, Bayero University Kano, Kano, Nigeria.*
**e-mail: s.robsan@gmail.com*

Published online: 27 February 2018
https://doi.org/10.1038/s41558-018-0098-9

References

1. Wise., R. M. et al. *Global Environ. Change* **28**, 325–336 (2014).
2. Mimura, N. et al. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability* (eds Field, C. B. et al.) 869–898 (IPCC, Cambridge Univ. Press, 2014).
3. Blair, T. *The Poverty of Planning* (Macdonald Publishers, London, 1973).
4. Fenton, P. & Gustafsson, S. *Current Opinion Environ. Sustain.* **26**, 129–133 (2017).
5. Simon, D. et al. *Environ. Urbanization* **28**, 49–63 (2015).
6. Sheppard, K. et al. *Nature* **523**, 152–154 (2015).
7. Stafford-Smith, M. et al. *Sustain. Sci* **12**, 911–919 (2017).
8. Reid, A. J. et al. *Environ. Sci. Policy* **77**, 179–184 (2017).
9. Le Blanc, D., Freire, C. & Vierros, M. *Mapping the Linkages between Oceans and Other Sustainable Development Goals: A Preliminary Exploration*. DESA Working Paper No. 148 (2017).
10. Massey, D. *For Space* (Sage, London, 2005).
11. Harvey, D. *Int. J. Urban Regional Res* **27**, 939–941 (2003).
12. Lefebvre, H. *The Production of Space* (Blackwell, 1974).
13. Lubchenco., J., Barner, A., Cerny-Chipman, E. & Reimer, J. *Nat. Geosci.* **8**, 741–745 (2015).
14. Allen, C., Metternichta, G. & Wiedmannbcet, T. *Environ. Sci. Policy* **66**, 199–207 (2016).
15. Carmin, J., Anguelovski, I. & Roberts, D. *J. Planning Education Res.* **32**, 18–32 (2012).
16. Vammen Larsen, S., Kørnøvb, L. & Wejsb, A. *Environ. Impact Assess. Rev.* **33**, 32–40 (2012).
17. Glass, E. & Juhola, S. *Sustainability* **5**, 256–275 (2013).
18. Mozumder, P., Flugman, E. & Randhir, T. *Ocean Coastal Management* **54**, 37–44 (2011).
19. *Designing Climate Change Adaptation Initiatives: A UNDP Toolkit for Practitioners* (UNDP Bureau of Development Policies, 2010).
20. *Local Governments and Disaster Risk Reduction: Good Practices and Lessons Learned* (UNISDR, 2010).
21. Acuto, M., Parnell, S. & Seto, K. C. *Nat. Sustain* **1**, 2–4 (2018).
22. Ürge-Vorsatz, D. et al. *Nat. Clim. Change* https://doi.org/10.1038/s41558-018-0100-6 (2018).

Turning Paris into reality at the University of California

The Paris Agreement highlights the need for local climate leadership. The University Of California's approach to deep decarbonization offers lessons in efficiency, alternative fuels and electrification. Bending the emissions curve globally requires efforts that blend academic insights with practical solutions.

David G. Victor, Ahmed Abdulla, David Auston, Wendell Brase, Jack Brouwer, Karl Brown, Steven J. Davis, Carrie V. Kappel, Alan Meier, Mark Modera, Rebecca Zarin Pass, David Phillips, Jordan Sager, David Weil and TomKat Natural Gas Exit Strategies Working Group

Over nearly three decades, diplomats and policymakers have been talking about global climate change while global emissions of warming gases have risen by one-third[1]. The 2015 Paris Agreement has offered an encouraging framework for reducing emissions. Yet pledges from countries under the Paris Agreement fall far short of the ambition to stop warming well below 2 °C above pre-industrial levels[2], and none of the large industrialized nations are on track to meet their pledges[3].

Such troubles have put a spotlight on the need for leadership institutions that are willing and able to achieve deeper and more rapid decarbonization. Those include university campuses, where there is often strong political pressure for action, along with large and diverse physical plants that offer a laboratory for experimentation. In California, a perennial leader on matters of global environmental policy, the largest of these campus efforts is at the University of California (UC), covering 10 campuses with more than 250,000 students. The university pledged in 2013 to become carbon neutral by 2025 (http://go.nature.com/2s8rXNr; ref. [4]). For the last two years, we have been part of an interdisciplinary team of academics and physical plant operators working in collaboration with university leaders and sponsored by the TomKat Foundation to investigate options for turning that pledge into reality[5].

The UC effort is now one of the most developed examples of the type of governance that the Paris Agreement was designed to spawn — decentralized, recursive, and aimed at finding and promoting best practices[6]. So far, more than 12,000 such initiatives have been registered under the Paris Agreement, but the UC system offers one of the most concrete models. By itself, the UC system can't solve the global problem — its emissions are just 0.005% of the total global emissions of carbon dioxide from burning fossil fuels. Through the Paris framework, if it fulfils its potential, leading efforts will be organized and evaluated in ways that can inspire others to look, learn and adopt.

The advantage of working out solutions in local settings is that there are strong incentives to experiment. In the UC system, the portable lessons are coming on three fronts — profound investments in efficiency, replacing conventional natural gas with even cleaner alternatives, and electrification. And like the rest of the world, the UC system is trying to do all this quickly, since emissions must turn downward rapidly to meet goals set by political leaders.

Leverage three ways

For now, the UC carbon neutrality pledge applies to direct emissions from UC-owned infrastructure and indirect emissions associated with the purchase of electric power. Indirect emissions from employee-owned vehicles, off-campus computing, air travel, and those embodied in consumed goods and services are subject to long-term goals but actionable plans will require more leadership.

Because the UC is focusing on its own emissions, gas is central. It accounts for 96% of emissions (Fig. 1a). About half

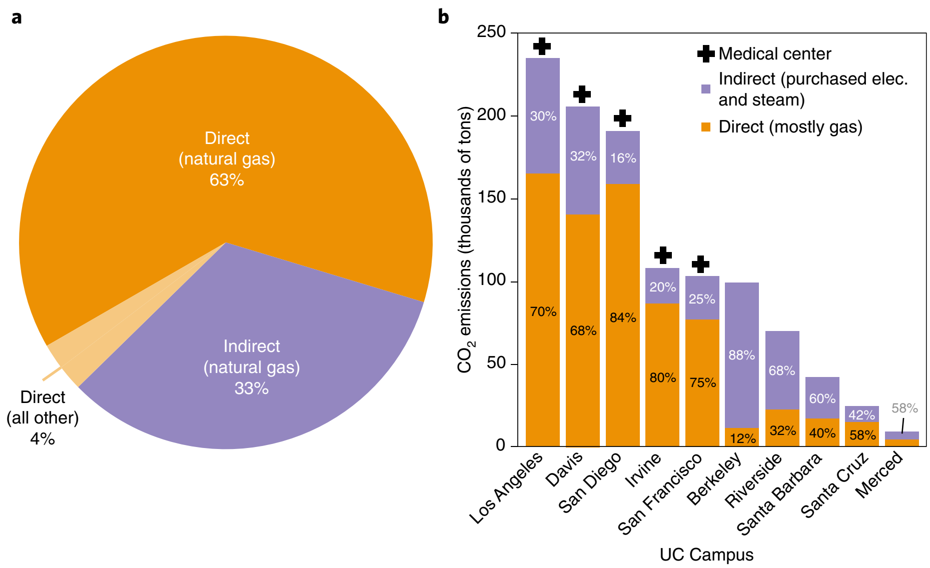

Fig. 1 | Emissions and natural gas consumption at University of California (UC) campuses in 2015. **a**, Natural gas burned on UC campuses accounted for 63% of the university's CO_2e greenhouse gas emissions, including both direct emissions (known as 'Scope 1') and indirect emissions related to purchased electricity and steam ('Scope 2'). **b**, The magnitude and share of natural gas emissions varies across the 10 UC campuses according to their size and climate, with all five of the largest campuses having medical centres (indicated by a cross) that create special energy needs.

the UC campuses have gas-fired power plants and combined heat and power (CHP) systems that save money through self-generation of energy services. The other half of the campuses are typically smaller, and most of their emissions come from purchased electricity[5]. In California, essentially all carbon emissions from the electrical grid come from burning

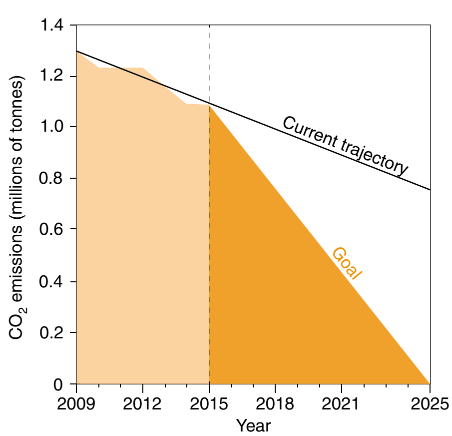

Fig. 2 | UC's recent rate of progress toward eliminating carbon from operations since 2009 (reliable data for all campuses is not available for prior years). Progress in bending the curve downward is anticipated in 2016 to 2018 based on solar PV coming on-line and biogas development. Additional acceleration of efforts will be required to reach carbon neutrality in 2025 (ref. [5]).

natural gas, which accounts for 60% of the state's power generation — the rest of the grid is operationally emissions-free. In California — and increasingly in the broader US power sector — decarbonizing electricity is about natural gas[7].

A three-pronged effort is underway to decarbonize UC emissions related to buildings that are familiar to almost everyone, such as offices, residences, and restaurants.

The first prong is efficiency (Ch. 2 in ref. [5]). All technically and economically realistic pathways to UC's carbon neutrality goal start with deep reductions in energy use, because well-planned energy efficiency investments pay for themselves through avoided energy costs. Since 2004, UC retrofit projects have reduced GHG emissions by an amount equivalent to 13% of 2015 emissions[8]. Most of this reduction has occurred since 2009 (Fig. 2), and the potential for further reductions is much larger. Relative to 2015, we estimate that further cost-effective retrofits could cut UC electricity use by 38%, and natural gas by 29%. Despite the existence of large, cost-effective efficiency measures, and the many encouraging moves to realize them[9], the gap between potential and reality remains huge.

A second prong is to replace conventional natural gas with less emission-intensive alternative fuels that would allow continued use of gas infrastructures — an option that is especially attractive at the seven campuses that currently operate central CHP systems where natural gas is burned to generate electricity and heat. For now, most eyes are on biogenic methane (biogas), produced today mainly by anaerobic decomposition of organic materials such as manure, food waste, agricultural wastes, fermentable landfill materials, and biosolids from wastewater treatment plants. The UC system already buys some biogas. For example, UC San Diego purchases biogas credits from a sewage treatment plant on Point Loma (about 15 km away) while burning conventional gas to power a fuel cell. More such biogas purchases are in planning, including two major deals in Wisconsin and Louisiana, which will supply carbon-neutral fuel to offset 10% of all natural gas currently burned on UC campuses.

There is a question of scalability around biogas. Our research suggests that all future biogas supplies, using known technologies and resources, may only provide about 4% of current national natural gas use (Ch. 4 in ref. [5]). With the right incentives, today's thin biogas market will yield new sources, but more work is needed to study the scalability of biogas — as well as the ecological consequences of large biogas operations — so that leadership with this option can translate into followership. Other promising ways to drop in replacements for conventional gas include hydrogen. If produced from zero-emission sources, it could supplement or replace conventional natural gas. A pilot project at UC Irvine is mixing small amounts of solar-produced hydrogen with the natural gas burned in its CHP facility[10].

That leaves the third prong: electrification (Ch. 4 in ref. [5]). Similarly to most campuses, the UC system is procuring more zero-emission electricity — in practice, an option typically implemented by purchasing wind and solar energy. UC's campuses now include over 50 megawatts of on-campus renewable electricity generation and 80 megawatts of utility-scale solar generation from sites in remote Fresno County. Buying zero-emissions electricity to supply existing power loads is relatively straightforward and does not raise many organizational or financial barriers. Converting on-site combustion of natural gas to electricity is financially more daunting.

For new buildings, the key to electrification is experimentation and demonstration with real projects. For example, a new 7,000-square-metre genomics laboratory at Lawrence Berkeley National Laboratory will use heat recovery chillers, air-source heat pumps, and point-of-use electric heat to provide all space and water heating needs without the use of natural gas. A few other campuses, such as UC Irvine and UC Davis, are implementing all-electric housing projects.

The defining problem for electrification is the use of electricity to provide heat at different temperatures. At most UC campuses, heating is the most carbon-intensive service provided, the largest fraction of GHG emissions, and the most significant opportunity for electrification. The major solutions are expensive (resistance heating), not suited for all purposes (hot water systems can't directly provide services such as sterilization that require higher temperatures), or finicky in operation (for example, heat pumps).

Real world experience suggests costs for new systems are manageable and perhaps cost-neutral for newly constructed buildings[11]. For existing buildings and infrastructure, the economics of electrification are still pretty ugly. Full electrification retrofits are difficult and electrification would strand large assets such as CHP plants.

Lessons learned

Many UC campuses are already doing a lot to control emissions, but so far those efforts have achieved only shallow decarbonisation, decreasing emissions per square foot of building area by about 25% from 2009 to 2015 (Fig. 2)[12]. Bending the curve more sharply requires both academic and practical insights. Academics have helped look far into the future at radical solutions, while operators of physical plants have helped ground that thinking in the real operational needs of buildings, as well as financing challenges.

Bending the emissions curve globally now requires that leaders work harder to create followers. Feeling good about local efforts to 'do something' about a global problem won't matter much, unless what is happening in California diffuses into practice far beyond its borders. After three decades of global talking without much action on climate change, the good news in Paris is that there is now a framework for leaders and followers alike to get serious about deep cuts in emissions. ❐

David G. Victor[1,2,3*], Ahmed Abdulla[1,2], David Auston[4], Wendell Brase[5], Jack Brouwer[6], Karl Brown[7], Steven J. Davis[8], Carrie V. Kappel[9], Alan Meier[10,11], Mark Modera[11], Rebecca Zarin Pass[10], David Phillips[12], Jordan Sager[13], David Weil[14] and TomKat Natural Gas Exit Strategies Working Group

[1]School of Global Policy & Strategy, University of California, San Diego, La Jolla, CA, USA. [2]Deep Decarbonization Initiative, University of California, San Diego, La Jolla, CA, USA. [3]The Brookings Institution, Washington, DC, USA. [4]Institute for Energy Efficiency, University of California, Santa Barbara, CA, USA. [5]Office of Sustainability, University of California, Irvine, CA, USA. [6]Mechanical and Aerospace Engineering, University of California, Irvine, CA, USA. [7]Berkeley Energy and Climate Institute, CITRIS and the Banatao Institute, University of California, Berkeley, CA, USA. [8]Department of Earth System Science, University of California, Irvine, Irvine, CA, USA. [9]National Center for Ecological Analysis and Synthesis, University of California, Santa Barbara, CA, USA. [10]Lawrence Berkeley National Laboratory, Berkeley, CA, USA. [11]University of California, Davis, CA, USA. [12]Office of the President, University of California, Oakland, CA, USA. [13]University of California, Santa Barbara, CA, USA. [14]University of California, San Diego, CA, USA.

TomKat Natural Gas Exit Strategies Working Group

Alan Meier[10,11], Steven J. Davis[8], David G. Victor[1,2,3], Karl Brown[7], Lisa McNeilly[15], Mark Modera[11], Rebecca Zarin Pass[10], Jordan Sager[13], David Weil[14], David Auston[4], Ahmed Abdulla[1,2], Fred Bockmiller[5], Wendell Brase[5], Jack Brouwer[6], Charles Diamond[13], Emily Dowey[16], John Elliott[10], Rowena Eng[13], Stephen Kaffka[11], Carrie V. Kappel[9], Margarita Kloss[10], Igor Mezić[13], Josh Morejohn[11], David Phillips[12], Evan Ritzinger[13], Steven Weissman[17] and Jim Williams[18]

[15]The City of Baltimore, Baltimore, MD, USA. [16]Department of Chemical Engineering, University of California Santa Barbara, Santa Barbara, CA, USA. [17]Goldman School of Public Policy, University of California Berkeley, Berkeley, CA, USA. [18]University of San Francisco, San Francisco, CA, USA.

**e-mail: david.victor@ucsd.edu*

Published online: 27 February 2018
https://doi.org/10.1038/s41558-018-0103-3

References

1. IPCC *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. et al.) (Cambridge Univ. Press, 2014).
2. *The Emissions Gap Report 2017* (United Nations Environment Programme, 2019).
3. Victor, D. G. et al. *Nature* **548**, 25–27 (2017).
4. *The University of California at a Glance* (University of California, 2017); http://go.nature.com/2Btxam6
5. Meier, A. et al. *University of California Strategies for Decarbonization: Replacing Natural Gas*; http://doi.org/ckjc (UC TomKat Carbon Neutrality, 2018).
6. Sabel, C. F. & Victor, D. G. *Climatic Change* **144**, 15–27 (2015).
7. *Natural Gas Consumption by End Use* (US Energy Information Administration, 2017).
8. Brown, K. et al. *Project Report — Deep Energy Efficiency: Getting to Scale (Lighting)* (Univ. California Global Climate Leadership Council, 2016).
9. *Overcoming Barriers to Carbon Neutrality* (Carbon Neutrality Finance and Management Task Force, 2017).
10. In a national first, UCI injects renewable hydrogen into campus power supply. *UCI News* (6 December 2016).
11. *Final Report — UC Carbon Neutral Buildings Study* (Point Energy Innovations, 2017).
12. *Annual Report on Sustainable Practices* (University of California, 2019).

Acknowledgements

We gratefully acknowledge the TomKat Charitable Trust, which provided funding to convene our working group, and UCSB's National Center of Ecological Analysis and Synthesis and Institute for Energy Efficiency, which co-administered the TomKat UC Carbon Neutrality project. Supplementary support was provided by the University of California Office of the President and by CITRIS and the Banatao Institute at the University of California. D.G.V. and A.A. were supported by the Deep Decarbonization Initiative of UCSD and by Electric Power Research Institute. S.J.D. was supported by NSF INFEWS Grant EAR 1639318. A.M. and R.Z.P. were supported by the Director, Office of Science, Office of Basic Energy Sciences, of the US Department of Energy under contract no. DE-AC02-05CH11231. We also thank the other members of the Natural Gas Exit Strategies Working Group: F. Bockmiller, J. Brouwer, C. Diamond, E. Dowey, J. Elliott, R. Eng, S. Kaffka, M. Kloss, L. McNeilly, I. Mezić, J. Morejohn, E. Ritzinger, S. Weissman and J. Williams.