International Institute for Applied Systems Analysis
IIASA www.iiasa.ac.at

Address: *IIASA, Schlossplatz 1, A-2361 Laxenburg, Austria*

Email: *permissions@iiasa.ac.at*

Working paper

The 'High-with-Low' Scenario Narrative: Key Themes, Cross-Cutting Linkages, and Implications for Modelling

Charlie Wilson, Arnulf Grubler, Gregory Nemet, Shonali Pachauri, Stefan Pauliuk, Dominik Wiedenhofer

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Approved by:

Name: Keywan Riahi
Program: ECE
Date: 9 August 2023

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Abstract

We define a global 'High-with-Low' scenario that delivers high wellbeing with low energy and material resource consumption while limiting global warming in line with Paris Agreement targets. The High-with-Low scenario comprises a rich thematic narrative and a quantitative framework for interpreting the narrative using systems and sectoral modelling tools at different scales. The three central themes of the High-with-Low scenario are decent living standards for all, innovation and granularity, and digitalization. Inter-linkages between these themes emphasize drivers of change towards a High-with-Low future that include decentralization, adaptability to local needs, accelerated diffusion through peer and network effects, and the management of complexity on shared infrastructures. However, the direction of change is not deterministic. The High-with-Low scenario envisages a set of specific and strong governance institutions for coordinating a highly distributed global sustainability transition. To help develop and enrich these narrative aspects, we also set out some guidelines and parameterisations for quantitative model interpretations of the High-with-Low scenario. These guidelines are not universally prescriptive but rather define a set of quantitative reference points against which model inputs, processes, and outputs can be iteratively tested for consistency. In particular, we emphasize the overall development pattern of the High-with-Low scenario as one of conditional convergence in which energy services for well-being increase substantially in the Global South catching up to levels maintained in the Global North, while associated resource use tends to converge, combining a contraction in the Global North with relatively modest increases in the Global South.

Acronyms

DLS	Decent Living Standards
HwL	High-with-Low
LED	Low Energy Demand

About the authors

The authors are all active members of the EDITS initiative (see Acknowledgements) in addition to their institutional affiliations.

Charlie Wilson is a visiting research scholar with the Energy, Climate and Environment program at IIASA, and a Professor of Energy and Climate Change in the Environmental Change Institute, University of Oxford, UK. (Corresponding author contact: wilsonch@iiasa.ac.at).

Arnulf Grubler is an emeritus research scholar with the Energy, Climate and Environment program at IIASA.

Greg Nemet is Professor at the University of Wisconsin–Madison's La Follette School of Public Affairs, Madison, USA.

Shonali Pachauri is a research group leader and principal research scholar with the Energy, Climate and Environment program at IIASA.

Stefan Pauliuk is Professor for Sustainable Energy and Material Flow Management at Freiburg University, Freiburg, Germany.

Dominik Wiedenhofer is a Senior Scientist at the Institute of Social Ecology (SEC) at the University of Natural Resources and Life Sciences, Vienna (BOKU)

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The High-with-Low scenario

Key concepts & terms

In this paper we define and enrich the narrative of a scenario that shows a world moving rapidly in the direction of the UN Sustainable Development Goals (SDGs), with a focus on rapid absolute reductions in resource use and GHG emissions.

Our scenario achieves high levels of human wellbeing that are more equitably distributed globally with significantly reduced energy and material consumption compared to today. Building off the global low energy demand (LED) scenario by Grubler, Wilson et al. (2018), our scenario paradigm can be summarized as **high** wellbeing with **low** resource use. This '**High-with-Low**' (HwL) juxtaposition reflects a central tenet of sustainable development: achieving high levels of human development while also preserving the natural environment by keeping the human resource use footprints within planetary boundaries (Rockstrom, Steffen et al. 2009, Rockström, Beringer et al. 2021, Fanning, O'Neill et al. 2022).

Our interpretation of sustainable development broadly follows the framework developed by Matson, Clark et al. (2016): "*Sustainable development aims to provide inclusive wellbeing, while increasing development capital and respecting planetary boundaries.*"[1] The focus on **well-being** recognizes both tangible and intangible constituents across material as well as social dimensions, both individual (health, education, opportunity) as well as collective (community, security). The term "inclusive" means wellbeing should be universal, i.e. achieved for all.

Services are another key concept in our High-with-Low (HwL) scenario narrative. Services refer to the amenities or functionalities like comfort, mobility, or social interactions that constitute well-being (Kalt, Wiedenhofer et al. 2019). Resource or economic inputs like income, energy, or materials (both as flows and stocks embodied in infrastructure) are needed to provide those services. This is an important distinction to traditional conceptualizations that equate well-being with levels of resource use (GDP or energy use per capita) (Haberl, Wiedenhofer et al. 2017, Lamb and Steinberger 2017).

[1] By increasing development capital we refer to the different forms of capital that are needed to run the economy and society, and which we leave behind for future generations enabling them to meet their own needs (Brundtland & Khalid 1987). Different forms of capital are needed for development: physical and economic capital including infrastructures and economic assets; human and social capital including educated work-forces and functioning social institutions; knowledge and innovation capital, an important resource to pass on to future generations; and natural capital including natural resources, environmental amenities, and ecosystem services. These different forms of capital are partially substitutable, partially complementary, and non-substitutable or with substitutability constrained by planetary boundaries and minimum requirements to safeguard ecosystem services (Rockstrom et al. 2009). Our interpretation of sustainable development therefore allows for non-renewable resources to be depleted, provided this does not infringe on planetary boundaries and socio-metabolic resource use is organized in a more circular and efficient manner. For example, copper extraction for electric and digital infrastructure is feasible if impacts are minimized on freshwater, land, biodiversity, and greenhouse gas emissions, and provided that extractive processes enable a significant build-up of physical, social, or knowledge capital for development, rather than just consumption activities.

Our emphasis on services is important for two reasons. First, it makes explicit that there is no fixed, constant relationship between levels of services delivered and their associated resource inputs; the relationship can be improved by increasing service efficiency. Second, focusing on services as outputs instead of physical or monetary inputs opens up thinking on alternative forms of service provision. The service of a comfortable home is a better descriptor for human well-being than the cubic metres of gas used to heat it, especially as the service can be provided alternatively by a building shell with weak thermal integrity and ventilation by leaky doors and windows, or by an efficient, well insulated building shell, and managed ventilation with energy recovery.

Positioning High-with-Low within the scenario literature

The High-with-Low (HwL) scenario is a development and enrichment of the global Low Energy Demand (LED) scenario (Grubler, Wilson et al. 2018). LED significantly pushed down the lower bound of energy consumption explored within global scenarios and modelling studies limiting warming to 1.5°C. Global final energy in LED by 2050 is 245 EJ, compared to median values of 442 to 544 EJ in 1.5°C scenarios with medium to high energy demand (Scott, Smith et al. 2022).

LED also helped establish demand-side transformation as an entry point for climate mitigation with stronger co-benefits than more conventional supply-side strategies, and significantly reduced reliance on carbon dioxide removal as a mitigation strategy. This perspective is not without its detractors: LED's emphasis on absolute demand reductions has been critiqued as a 'Goldilocks' future that improves living standards in the Global South without acknowledging the need for resource-intensive industrial and economic development (Semieniuk, Taylor et al. 2021). Energy demand reductions also meant LED was characterised as having low social and institutionally feasibility within recent multi-criteria feasibility assessments of mitigation scenarios (Brutschin, Pianta et al. 2021).

As an alternative long-term scenario paradigm, LED has been used as a reference scenario or illustrative mitigation pathway in IPCC reports including the Special Report on Global Warming of 1.5°C (Rogelj, Shindell et al. 2018) and the Sixth Assessment Report[2] (Riahi, Schaeffer et al. 2022). LED-type narratives have also been interpreted in national scenario modelling studies including in France and the UK (négaWatt 2017, Barrett, Pye et al. 2022).

The HwL scenario narrative's emphasis on providing high levels of wellbeing while minimizing resource use follows the tradition of efficiency scenarios that focus on service delivery through radically improved technological, institutional and social provisioning systems. These were first introduced as 'soft' development paths by Amory Lovins back in 1976 (Lovins 1976). Subsequent studies further developed efficiency pathways within a wider set of scenarios including the 'C' scenarios of the World Energy Council (Nakicenovic, Grubler et al. 1998), the 'B1' scenarios of the IPCC Special Report on Emissions Scenarios (Nakicenovic, Alcamo et al. 2000), and the 'Efficiency' scenarios of the Global Energy Assessment (Johansson, Nakicenovic et al. 2012).

[2] P1 in the Special Report on 1.5°C, and IMP-LD (Illustrative Mitigation Pathway – Low Demand) in the Sixth Assessment Report.

Importantly, however, the current SSP (shared socioeconomic pathways) framework used in the IPCC and other contexts (O'Neill, Kriegler et al. 2016) does not represent soft or efficiency pathways nor associated policy strategies. This omission triggered the development of LED, and now HwL, as a necessary contrasting perspective to broaden out the future possibility space explored by long-term scenario thinking. As such, the HwL narrative should not be misinterpreted as simply another incarnation of the 'green growth' SSP1 scenario as its narrative elements are quite different, relying not on enlightened environmentalism and shifting values, but on bottom-up drivers of development and living standards.

HwL should also not be interpreted as a narrative for an (economic) **degrowth** scenario (Victor 2012, Kallis 2017). HwL intentionally makes no reference to classical economic scenario variables such as GDP as these cannot adequately capture many salient elements of HwL (e.g., wellbeing, social innovation, lifestyle changes, novel forms of service provisioning operating outside classical commodity markets). Additionally, while resource inputs in HwL are drastically decoupled from service levels globally, in the Global North service levels (i.e., outputs) remain high or even slightly increase, but they grow substantially in the Global South. This is contrast to the principles underlying current "degrowth" debates (Hickel, Kallis et al. 2022).

Energy and **materials** are the principal natural resources considered in the HwL scenario and in the LED study, but – as the LED name suggests - with greater emphasis on energy in the quantitative interpretation using MESSAGE, an energy systems-based integrated assessment modelling framework (Grubler, Wilson et al. 2018). This is not to downplay the importance of the **material** dimensions to low resource futures. Industrial output accounts for around one quarter of global GHGs through the processing of materials into products, stocks, and infrastructures which in turn shape and lock-in future energy needs (Hertwich 2021, Lamb, Wiedmann et al. 2021). Other **material** stock-flow modelling analyzes provide complementary insights to LED on the material implications of climate change mitigation pathways (Krausmann, Wiedenhofer et al. 2020), including those that explicitly interpret the LED scenario through a material lens (Fishman, Heeren et al. 2021, Pauliuk, Heeren et al. 2021). Additional complementary studies have also elaborated on the material and infrastructure needs for decent living standards worldwide (Fisch-Romito 2021).

Studies focused more explicitly on the material dimensions to low resource futures draw on circular economy concepts to 'narrow, slow, and close' material loops through better design, lightweighting, and dematerialization (narrow), extending product durability and longevity (slow), refurbishment and recycling (close) (Bocken, de Pauw et al. 2016). In general, circular economy strategies reduce both raw material and energy resource use, but not in all cases (Hertwich, Ali et al. 2019, Cantzler, Creutzig et al. 2020). The 'narrow, slow, close' taxonomy for material-focused mitigation strategies are aligned with the transformative approach to planetary socio-metabolism represented in HwL with its emphasis on service efficiency and dematerialization alongside step change efficiency improvements in resource use within service provisioning systems.

Central themes of the High-with-Low scenario

The global LED study that provides the start point for this High-with-Low scenario emphasized five 'mega-trends' shaping energy system development to 2050: urbanization; new forms of energy service provision; user-oriented innovation, particularly through ICTs; diversification of end-user roles; improving quality of life

(Grubler, Wilson et al. 2018). The global LED scenario also centerd around five more specific drivers of change: rapid transformation; decentralized service provision; granularity; digitalization of daily life; and a shift from owning to accessing.

In the High-with-Low (HwL) scenario narrative, we extend and enrich the global LED study in three important ways. First, we expand on the importance of three underpinning and inter-related themes: **decent living**, **innovation**, and **digitalization**. Each of these themes has a strong connection to the global LED scenario, and have seen significant progress in both practice and research in recent years – as examples: decent living in the SDG agenda; innovation in the exponential cost declines observed in solar PV, batteries, and electronics; and digitalization through pandemic experiences of service provision rapidly shifted online. We also show and discuss how these three themes inter-link in synergistic ways to ensure a resource-efficient future with high and inclusive wellbeing (Figure 1).

Second, we more explicitly consider the policy, **governance**, and coordination challenges associated with delivering High-with-Low transformational change while mitigating risks and adverse impacts of a highly distributed program of social, technological, and behavioral solutions.

Third, the global LED scenario and modelling – in common with most of the mitigation pathway literature – analyzes technological change in more detail than **social and institutional change**, despite their inseparability in practice. Here, we try and expand as much as possible on the social, behavioral, and organizational implications of a High-with-Low future.

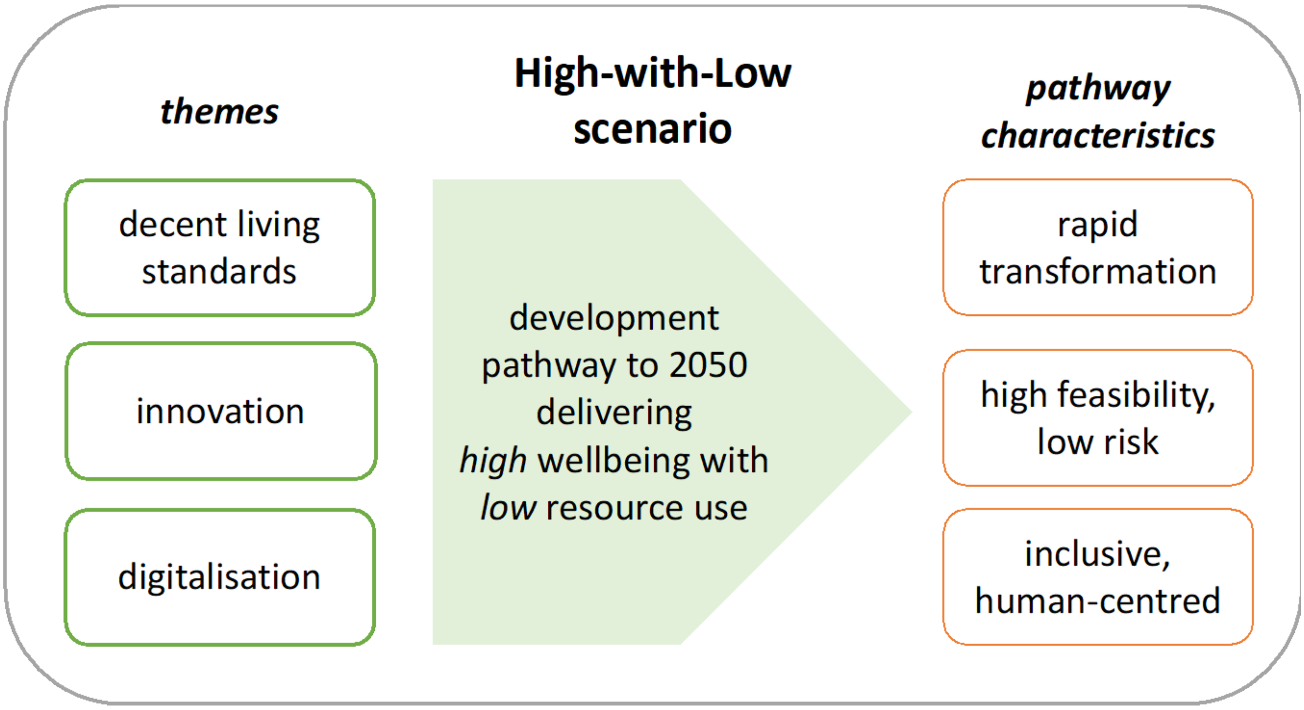

Figure 1. Three main themes in the High-with-Low scenario, and characteristics of the resulting development pathway to 2050.

Decent living for all

First and foremost, the High-with-Low scenario describes a more equitable, fair, and inclusive future, with climate and other environmental goals embedded within a broader sustainable and social development agenda. Such a future acknowledges the value of every human being and grants all individuals the right to a **decent life** based on a common and shared responsibility towards other human beings and the planet, both today and into the future. Providing a decent life for all by eliminating all forms of extreme deprivation, under-consumption, and exclusion, has been endorsed globally as desirable on normative grounds including in the targets and goals set by the UN 2030 Agenda (United Nations 2020). Understanding has steadily grown for how poverty eradication enables a larger share of the population to live healthier lives, participate in labor markets, increase productivity, generate employment, improve livelihoods, increase agency and voice, reduce deaths and disability, enhance public acceptability of climate and environmental policies, and become self-reliant (World Bank 2005, SEforALL 2017, Barnes, Samad et al. 2018). The vast global pool of un-served consumers also represent an immense unexploited market (Prahalad, Prahalad et al. 2005). Alleviating multidimensional poverty and deprivations reduces vulnerability to climate impacts, disasters, and other shocks, as well as the threat of terrorism, conflict and migration (Hallegatte and Rozenberg 2017, Hallegatte, Fay et al. 2018, Bastia and Skeldon 2020).

Ensuring a decent standard of living for all need not be tied to an ever-expanding set of material consumables that are privately owned. What constitutes a good life, a decent life, a good quality of life, wellbeing, happiness, human flourishing, a life that deprives no one of their ability to meet basic needs and more, have long been debated (Rawls 1971, Doyal and Gough 1991, Max-Neef 1991, Nussbaum 2003, Costanza, Fisher et al. 2007). We follow Rao and Baer (2012) and Rao and Min (2017) in defining **decent living standards (DLS)** as "*a set of universal, irreducible and essential set of material conditions for achieving basic human wellbeing, along with indicators and quantitative thresholds, which can be operationalized for societies based on local customs and preferences*". Importantly, DLS constitutes a minimum threshold or floor to consumption that is required for ensuring human wellbeing for all.

This is distinct from the idea of a consumption corridor defined by both a minimum and maximum threshold to consumption or sufficiency (Di Giulio and Fuchs 2014, Lamb and Steinberger 2017, Fuchs, Sahakian et al. 2021). Despite renewed attention on and importance of **sufficiency** (see Box 1), the High-with-Low scenario does not define any maximum thresholds or ceilings. This is also because how to quantify such a sufficiency ceiling remains contested and existing examples are limited and very context specific to date.

The DLS framework identifies groups of basic needs with sub-dimensions for which energy and material prerequisites can be estimated. Physical needs include shelter (housing, indoor comfort), nutrition (food), health and hygiene (water, sanitation, health care). Social needs include socialization (education, social connectedness), mobility (physical connectedness). This is not to imply that non-material needs or intangibles are any less essential to a decent life. Being part of a community, having a say in the shaping of society, feeling and being safe and secure, being able to express identity are also important "protected needs" (Di Giulio and Defila 2019). However, as meeting these needs does not have significant material and resource consequences, they are not the focus of the High-with-Low scenario.

Evidence is growing on opportunities to limit growth of global energy and material demands while meeting decent living standards for all and improving human wellbeing (Brand-Correa and Steinberger 2017, Haberl, Wiedenhofer et al. 2017, Lamb and Steinberger 2017, Creutzig, Niamir et al. 2021, Gillingham, Huang et al. 2021). How essential human needs are met also has wellbeing implications that depend on how efficiently resources and materials are used, how service provisioning systems are designed (Plank, Liehr et al. 2021), how social norms and cultures shape use, and whether associated waste and emission streams from socio-metabolic systems impact human and planetary health (Pauliuk and Hertwich 2015, Haberl, Wiedenhofer et al. 2019) (Figure 2).

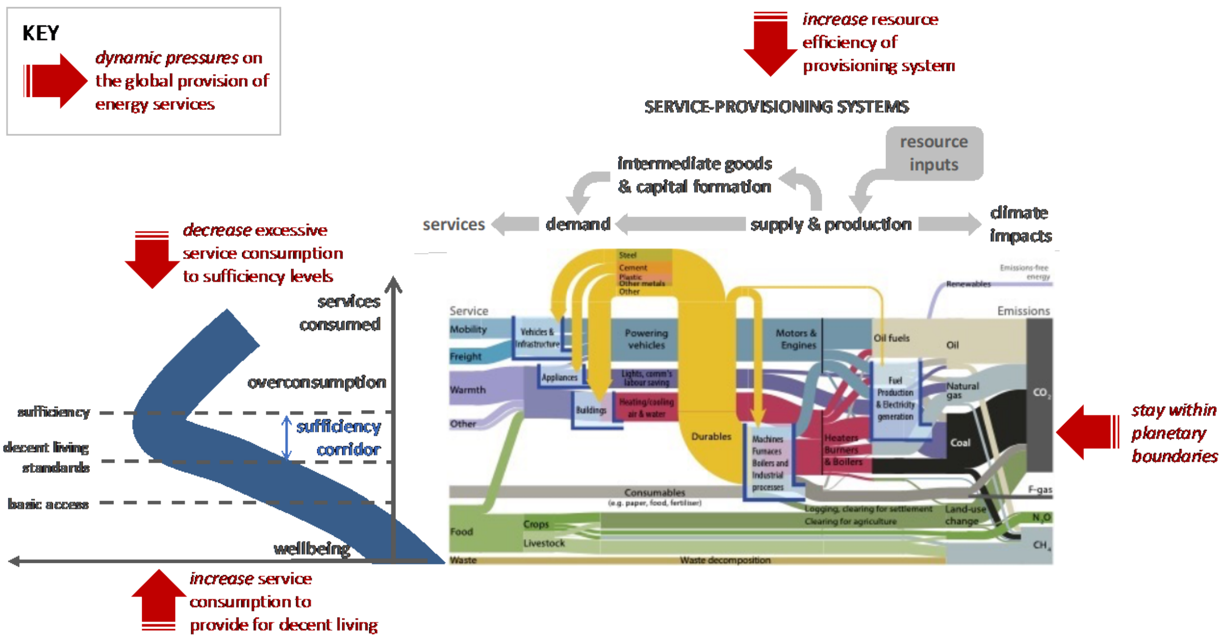

Figure 2. Transforming how services are provided to meet human needs with fewer resource inputs. Left panel shows stylized relationship between levels of service provision and human wellbeing. Right panel shows the resource processing flows (Sankey diagram) through the global service provisioning system using data for 2010, from Bajželj, Allwood, and Cullen (2013). Thick red arrows show dynamic pressures to deliver High-with-Low outcomes. Source: Wilson, Grubler et al. (2023) based on TWI2050 (2020).

BOX 1. The importance of sufficiency: Defining floors and ceilings.

Sufficiency in Latin means “enough”. The concept has been in focus recently in discussions of ways to transform our societies to sustainable and low-carbon futures (Burke 2020, Defila and Di Giulio 2020, Akenji, Bengtsson et al. 2021, Fuchs, Sahakian et al. 2021). Sufficiency is clearly normative in that it targets both under- and over-consumption, and so focuses on defining lower and upper consumption thresholds that both achieve human wellbeing in an equitable manner and within environmental and planetary limits. It builds on recent work on how to define and quantify a floor or minimum threshold of material needs necessary for human wellbeing (Rao and Min 2017, Rao, Min et al. 2019, Kikstra, Mastrucci et al. 2021), and growing evidence that ever-increasing consumption does not bring ever higher levels of happiness or wellbeing and threatens the health of the planet and global ecosystems (Wiedmann, Lenzen et al. 2020, Rao and Wilson 2022).

While there have been advances in defining and measuring a floor or minimum threshold to consumption that is universally applicable, efforts to define and quantify a ceiling or maximum threshold have so far been very limited and context specific. An early practical example of defining a sufficiency ceiling for consumption is the 2000-Watt Society initiative in Switzerland (Spreng 2005). More recently, the French Negawatt association has combined the three pillars of sufficiency for avoided consumption or demand, efficiency for reduced material and energy intensities, and renewables for decarbonization to develop an energy transition scenario for France (négaWatt 2017).

Despite recent conceptual and scientific advances in how to define and measure sufficiency, much remains to be answered in how to specify and quantify limits of consumption. Importantly, increased understanding of underlying drivers of overconsumption is also needed to overcome opposition to and increase acceptance of ‘sufficiency’ lifestyles.

Innovation

Innovation is integral to the High-with-Low scenario because limiting warming to 1.5°C while universally providing for human needs within planetary boundaries requires very rapid rates of change. New resource-efficient technology enabled by digitalization and providing new services amidst changing end user roles has to play a central role.

Consequently, a central feature of the High-with-Low scenario is that innovation must accelerate and must be directed or governed. At a macro level, global improvement in energy efficiency (energy/GDP) will have to increase from its recent rate of -1.3% per year from 2016-21 to triple that rate from 2020-30 (IEA 2021). This in turn means an acceleration in rates of resource-efficient technology adoption: from building efficiency retrofit and low-carbon heat technology adoption to vehicle substitution and active travel or shared mobility uptake.

The distinct characteristics of resource-efficient innovation in the HwL scenario also make it amenable to acceleration (Box 2). Solutions tend to be smaller scale, more distributed, and more modular - what we call 'granular' (Wilson, Grubler et al. 2020). Examples include: building insulation, , non-motorized and shared mobility schemes, dietary changes, efficient appliances, distributed supply and storage technologies like PV panels, fuel cells, and batteries.

Smaller scale technologies show both faster learning (Sweerts, Detz et al. 2020) and more rapid diffusion (Wilson, Grubler et al. 2020). In addition, the emergence of digitalization as a general purpose technology provides an array of new possibilities across service provisioning systems linked to DLS (Wilson, Kerr et al. 2020), particularly in terms of new services for heterogeneous end-user preferences and adoption niches. Rapid learning in combination with the flexibility that granularity provides may be especially important in providing new services to help populations attain decent living standards (Poblete-Cazenave, Pachauri et al. 2021, Semieniuk, Taylor et al. 2021). Granular solutions combine scalability with customization, so can better serve the rising demands for decent living that the High-with-Low scenario implies.

Box 2. Distinct characteristics of innovation in the High-with-Low scenario.

Multiple attributes and new services. LED innovations do not simply replace energy-intensive practices but can provide multiple and novel services (Fishman, Heeren et al. 2021).

Many heterogeneous adopters. The diversity of individual preferences and local contexts matter, particularly in developing country contexts where pursuit of decent living standards shifts priorities and design trade-offs for innovation (Ockwell, Sagar et al. 2015).

Evolving social preferences. Some emerging indicators include shifts to valuing low-consumption lifestyles (Garnett, Balmford et al. 2019).

Peer and network effects. Being able to access information from trusted sources (peers) can mitigate risk aversion in technology adoption and can catalyze later stage epidemic-type technology adoption (Fletcher and Ross 2018, Wolske, Gillingham et al. 2020). Similarly network effects by which one person's adoption of a technology enhances the value of it for others can further accelerate innovation (Kubli and Ulli-Beer 2016, Li, Tong et al. 2017).

Small-scale, 'granularity'. Consequences of LED innovations being small scale include lower adoption risk and more flexibility (Wilson, Grubler et al. 2020), especially with many heterogeneous adopters and of particular importance in DLS adoption contexts.

Many iterations. Technologies and behaviors can be expected to change and improve considerably leading to rapid learning (Nemet 2019). Short lifetimes of some LED innovations enable more rapid replacement of energy-intensive capital stock (Tong, Zhang et al. 2019) and an entry for novel LED practices in the medium-term.

Local system integration. Necessary for widespread uptake of LED innovations, while allowing for creative use of unique adoption contexts taking advantage of the flexibility that granularity provides (Jain, Qin et al. 2017).

Rebound effects. LED practices can become used so much that some of the resource-efficient gains are offset, although policy can mitigate this effect (Gillingham, Kotchen et al. 2013, Stern 2020).

All of these changes require a strong role for governance in guiding the direction of innovation toward HwL outcomes, as well providing infrastructural support (Nemet and Greene 2022). Social and business model innovation, typically in combination with hardware and digital innovation, is central to the High-with-Low scenario because: it provides the means for rapid transformation; it encapsulates a dynamic view on LED technology, behavior, and adoption; and it reconciles DLS goals with other aims of the High-with-Low scenario. High-with-Low therefore sees the widespread adoption of existing resource-efficient practices, broadening to new geographies and new users, as well as novel combinations of behavior, technology, and business models. Box 3 provides some illustrative examples.

All this falls under the rubric of what we mean by **innovation**: improvements and widespread adoption of resource-efficient practices, including hardware, software, and 'orgware' - the institutions and social practices that shape the use of technology. A salient interpretation of the innovation history since the onset of the Industrial Revolution points to the critical interplay between innovations in hardware on the one side and software and orgware on the other (Grubler, 1998). Institutional, social, and economic settings provide the environment and incentives in which hardware innovations can be developed. They are also critical in governing the adoption of innovations and for ensuring associated learning and experimentation. Innovation agents (producers and users) do not operate in a vacuum, but in social, economic and institutional contexts that influence their behavior and interactions. In turn, cross-cutting innovations such as digitalization can drastically change the way innovation agents act and interact, enabling improved coordination and accelerating collective learning processes that are key to a rapid sustainability transition.

Box 3. Examples of intertwined technological and social innovations in the High-with-Low scenario.

Combinations of social, behavioral, business-model, and technological innovations have the potential to deliver HwL outcomes (Niamir, Verdolini et al. 2023). Three illustrative examples are:

Additive manufacturing. Also known as 3D printing, this term refers to a range of manufacturing methods where metallic, ceramic, or plastic objects are fabricated using a computer-based design and typically applied in layers of material. They have the potential to deliver customized products with reduced shipping energy and less material.

Shared mobility. Here mobility services are provided by means of a shared asset (e.g., a bicycle, e-scooter, vehicle) combined with the use of hardware devices and software to connect users and providers. It was the potential to reduce both energy and material demand.

Solar prosumers. These households both consume and produce energy services and consequently have strong potential to reduce energy demand because transmission losses are avoided and waste heat is not generated.

In all cases, there is strong potential for widespread adoption of these approaches, subject to a set of eight social enablers or conditions needed to unlock innovation pathways: behavior and lifestyle changes; peer effects; inclusive governance; infrastructure design and availability; finance and investment; market development and cost reductions; regulations and policies; and novel business models (Niamir, Verdolini et al. 2023).

Digitalization

Digitalization is a rapid and pervasive secular trend transforming society (e.g., media, networks, platforms) and the economy (e.g., automation, cloud-based services, artificial intelligence). Digitalization has large potential benefits for sustainable development (e.g., collective intelligence, access to opportunities, system efficiencies) but also major risks (e.g., value polarization, precarious employment, material resource extraction) (WBGU 2019). Harnessing digitalization as an enabler of transformation therefore requires clear direction, coordination and governance. Under appropriate conditions, **digitalization** can enable more services for fewer resource inputs in a High-with-Low future (Box 4). Digitalization enables or creates new forms of resource-efficient services (e.g., shared ride hailing), new substitutes for physical activities (e.g., teleworking, online retail), new ways of organizing, sharing, and coordinating daily life (e.g., sharing economy platforms for waste reduction), and new opportunities for optimizing service provision (e.g., multi-modal transport systems) (Royal Society 2020, Wilson, Kerr et al. 2020, Creutzig, Roy et al. 2022). The co-design of digital transformation and sustainable development strategies is essential for steering the rapid ongoing digitalization of social and economic processes towards High-with-Low goals (Digitalization for Sustainability (D4S) 2022, Pauliuk, Koslowski et al. 2022).

Digitalization interacts strongly with innovation and decent living - the other two main themes of the High-with-Low scenario. Involving software and digital devices in service provision has the additional benefits of rapid innovation cycles through experimenting, testing, learning, and improving that are associated with both digital and granular technologies. Data-rich systems for providing or improving shelter, nutrition, health, socialization, and mobility allow for greater differentiation of services to provide DLS across diverse user groups and contexts. As examples: (1) mobility-as-a-service concepts allow different transport modes to be combined in real-time to suit users' particular travel needs; (2) e-health services bring specialist expertise to areas lacking healthcare infrastructure; (3) energy management systems added to existing homes and commercial buildings help control and reduce demand; (4) digital platforms improve social connectedness and rapid information dissemination on what HwL solutions and policies work. (See also Box 4).

Digital platforms also support community organizing to support service delivery (e.g., food-sharing networks or local food hubs) and retain employment opportunities in diversified service sectors (e.g., skills-matching platforms, P2P and sharing economy business models). Community-based service provision is an important alternative to centralized delivery models led by the state or public utilities in countries or contexts with low institutional trust or capacity.

Box 4. Examples of High-with-Low solutions dependent on, or enabled by, digitalization.

Mobility. Shared vehicle fleets with higher occupancy rates and reduced trip times due to lower congestion are enabled by digital platforms connecting surplus capacity with real-time demands, and adaptively re-routing vehicles to maximize system efficiencies and occupancy rates (ITF 2017). This also requires clear governance approaches to co-design technologies (e.g., vehicles), infrastructures (e.g., public transit systems), market incentives and regulation.

Mobility. Smart charging of electric vehicles provides a distributed storage resource for electricity network operators to draw on during peak periods in an 'vehicle-to-grid' configuration enabled by digital information flows and charging control systems (Thompson and Perez 2020).

Health, work and leisure. Teleworking, teleconferencing, and virtualization of health and education services (all spurred by the pandemic) offer substitutes for energy-intensive travel.

Consumer goods. Dematerialization through 'functional convergence' of multiple services and applications onto single digital devices (phones, tablets, laptops) acting as gateways to cloud-based service provision (Ryen, Babbitt et al. 2015, WEF 2019).

Thermal comfort. Smart home technologies and home energy management systems configured to optimize heating and cooling for domestic comfort, maximize own-consumption of domestic electricity production, learn about domestic routines, and avoid wasted heating or cooling in occupied homes (AlFaris, Juaidi et al. 2017, Wilson, Hargreaves et al. 2017, Kloppenburg and Boekelo 2019).

Logistics. Data-rich optimization of intra-urban logistics operations for products, deliveries, mail, food and waste can help improve overall system efficiencies and reduce resource demands.

Cross-cutting linkages between themes

The three themes central to the High-with-Low scenario interact to generate a number of cross-cutting linkages (Figure 3). In a High-with-Low future, these linkages are synergistic and supportive of resource-efficient outcomes and inclusive wellbeing. However, these outcomes are not deterministic, and indeed, the center of Figure 3 emphasizes the importance of coordination and governance in achieving the High-with-Low scenario. The same cross-cutting linkages in the absence of strong governance institutions could generate inequalities, exclusion, extractive resource dependence, and trade-offs between SDGs.

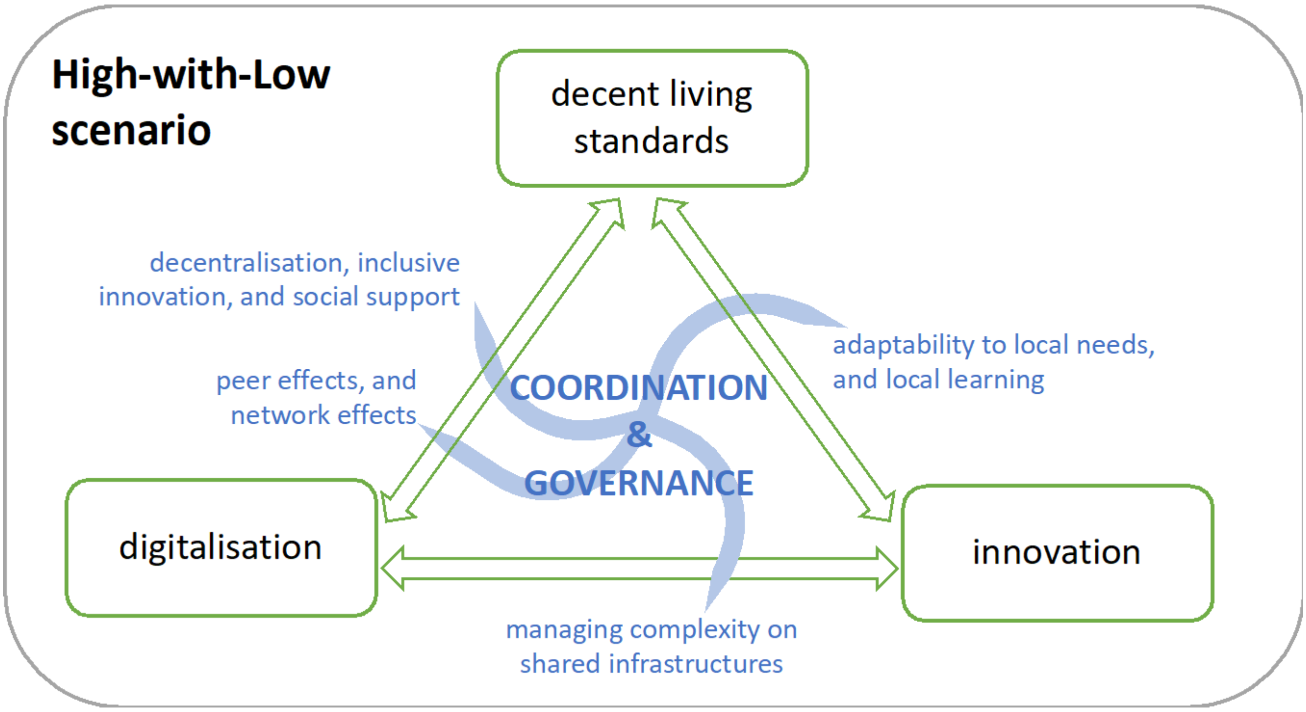

Figure 3. Cross-cutting linkages between the three central themes of the high-with-low scenario.

Decentralization, inclusive innovation, and social support mechanisms

Appropriate innovation and digitalization enable multidimensional poverty eradication. As early as the 1970s, appropriate technology was seen as a way to deliver community empowerment and promote local ingenuity (Smith 2005). This followed from Boserup's work providing evidence of innovation processes in primitive agricultural settings, leading her to conclude: "*The power of ingenuity would always outmatch that of demand*" (Boserup 1976). More recently, the concept of **inclusive innovation** has gained traction: "*development and implementation of new ideas which aspire to create opportunities that enhance social and economic well-being for disenfranchised members of society*" (George, McGahan et al. 2012). Similar concepts, such as frugal innovation, have also been highlighted in the literature as important for repurposing existing resources or using locally abundant or discarded resources to deliver low-cost services to meet needs of remote and low-income populations affordably (Hossain 2022).

Within a High-with-Low framing of the future, achieving DLS for all requires rethinking innovation processes and harnessing digital technologies for this purpose. This has three main elements: decentralization; inclusive innovation; and social support mechanisms.

First, there is a need to re-examine the role of incumbent large-scale centralized modes of infrastructure and service delivery that have a tendency to concentrate benefits and become inert to change. A shift from the existing top-down supply-focused privatization and commoditization of knowledge to more inclusive forms of innovation that harness local ingenuity will be required (Brand, Muraca et al. 2021). High-with-Low innovation includes that which originates from, and operates in, civil society. This is more localized, context specific, and socially determined (Vogel, Steinberger et al. 2021). In a High-with-Low future, more granular technologies and more **decentralized** service-provisioning systems allow for greater diversity and choice in modes of provisioning, and an agility that can accelerate DLS for all.

Second, service provisioning to meet DLS for all has to be more **inclusive** for both consumers and producers or suppliers. A larger role for community-based organizations, social enterprises, and prosumers (actively participating end-users) can extend services and integrate excluded populations. A good example is how low-cost solar-based lighting technologies and solar panels are diffusing widely in sub-Saharan Africa. In Bangladesh, 'swarm electrification' approaches allow for the linkage of individual stand-alone energy systems to form microgrids that can eventually even interconnect with national or regional grids (Dumitrescu, Groh et al. 2020). This inclusive form of innovation shows how network effects are generated through the inclusion of localized economies with strong producer-consumer linkages embedded within larger systems of trade and exchange. Digitalization can also support and enable sharing economy practices and user-led innovations that can help reduce or avoid waste by redeploying surplus capacity in real-time (e.g., ridesharing, shared ride-hailing, P2P carsharing, crowdsourced finance or work-time resources, food sharing, community fridges). More broadly, digitalization also has the potential to democratize the provision of DLS. For instance, e-learning and e-health platforms can enable information flows and more equitable access to public services (e.g., mobile-based reminders to patients to take medication, greater interaction with teachers and health professionals) (Sharma and Sturges 2007). Digitalization can also support new processes, increase efficiency and transparency, and allow for participation in existing markets and processes, and thus drive competitiveness and shape patterns of development towards greater equity, inclusiveness and sustainability (Figueres 2013). A specific example is how mobile phones are used by remote micro-entrepreneurs to contact customers (Donner and Escobari 2010).

Third, although innovation and digitalization can help make services more affordable, short-term subsidies or **social support mechanisms** will still be required to ensure access for all. Business model innovation is also needed to convert prohibitively high upfront costs into smaller streams of payment. Examples of this already happening is visible in Africa and other developing regions with mobile-based apps such as M-Pesa and Hello Tractor which are enabling greater access to financial services that were out of reach for remote, underserved, or low-income communities (Box 5).

Appropriate governance institutions or coordination mechanisms are also needed to avoid exploitative practices in the sharing economy (Acquier, Daudigeos et al. 2017). Digital platforms benefiting from strong network externalities leading to dominant market positions (e.g., AirBnB, Uber) move away from principles of sharing surplus resources to market-logics of new private service provision (Frenken 2017).

Box 5. Examples of innovations harnessing digitalization to support DLS for all.

Hello Tractor. The so-called 'Uber for farmers', Hello Tractor aims to provide many agricultural workers with access to previously unaffordable technology. It is a mobile phone app through which farmers can hire mechanized farming equipment in several African nations.[3]

M-Pesa. A financial service, developed in Kenya, allows mobile device users without bank accounts access to: credit and savings; payment for products and services; and deposits, withdrawal and transfer of money from a network of agents that includes airtime resellers and retail outlets acting as banking agents. Its positive effects include creating money flows to rural areas, where cash is difficult to access and increasing the financial autonomy of women (Morawczynski and Pickens 2009).

Adaptability to local needs, and local learning

HwL solutions tend to be demand-focused, human-scaled, and granular. As noted earlier, smaller unit scales enable rapid experimentation and learning, as well as adaptation possibilities for diverse market and social conditions. Customization and local learning involves the adaptation of globally generated innovations (both hard and soft) to the needs and idiosyncrasies of local adoption contexts. Benefits are often multiple and valued differently among adopters. This adaptation typically involves a process of local learning, in which a variety of actors pay a role in integrating novelty into the local culture, behavior, and technological systems. A particular focus in High-with-Low is the reorientation of local learning to the diverse set of needs around supporting DLS. This raises questions about how innovation systems can evolve to harness local knowledge. Rapid learning in combination with the flexibility that granularity provides may be especially important in providing new services to help populations attain DLS (Poblete-Cazenave et al. 2021; Semieniuk et al. 2021). This enhances their social legitimacy and acceptance, supporting accelerated diffusion. Digitalization means that small pilot examples oriented toward DLS can be improved, scaled-up quickly, and transferred to other locales, for example via sharable computer code, product designs, and easy language translation.

At the same time, innovation processes with increasing returns to scale, and digitalization with its characteristic network effects, are dependent on standardization and serialization for rapid dissemination through replication as already evidenced in PV and battery technologies. But the granular nature of these technologies still allows for their adaptation to diverse settings including market sizes (magnitude of local energy demand), system configurations (local energy networks), consumers' engagement (prosumers), or innovative financing opportunities (cooperatives or crowd funding schemes). These examples highlight again the intertwined social, technological, and business model characteristics of High-with-Low.

Peer effects, and network effects

Realizing the potential of HwL innovations depends on speeding up the processes of technology development, adoption, and integration with surrounding technological systems and infrastructures, such that the beneficial impacts are pervasive and inclusive. Accelerated HwL innovation can initiate via catalytic mechanisms (Catalini and Tucker 2016, Farmer, Hepburn et al. 2019) and scale via increasing returns (Arthur 1989, Ma, Grubler et

[3] https://stories.cgtneurope.tv/hubs/innovation-action-change/can-technology-end-poverty/index.html

al. 2009). Examples of catalytic mechanisms include peer effects, and examples of increasing returns include network and learning effects (Kubli and Ulli-Beer 2016, Li, Tong et al. 2017). An iterative process of experimentation can occur locally and address the diverse set of needs to support DLS.

First, peer effects, enabled by digitalization, facilitate the recognition and communication of the benefits of HwL practices among typically risk-averse adopters (Guadalupi 2018, Wolske, Gillingham et al. 2020). Being able to access information from peers as trusted sources can mitigate risk aversion in technology adoption (Rai and Robinson 2013) and in later stages can catalyze epidemic-type technology adoption if experiences communicated through inter-personal networks are positive (Fletcher and Ross 2018, Wolske, Gillingham et al. 2020). Peer effects reduce barriers to adoption by providing easy to access trusted information about HwL innovations (Qiu, Yin et al. 2016). Peer effects have been observed both in terms of assessing outcomes (Bollinger and Gillingham 2012, Korcaj, Hahnel et al. 2015) and also by directly asking about them as a motivation (Palm 2017). Digitalization facilitates catalytic and increasing adoption dynamics via granularity and flexibility, in addition to enhancing knowledge flow directly (through electronic word-of-mouth, social media). In pursuit of DLS, peer effects have also been important among low-income adopters but have required policy to catalyze (O'Shaughnessy, Barbose et al. 2021).

Second, network effects, enhanced via standardization create the potential to accelerate HwL innovation by increasing the appeal of HwL behaviors and systems over time. Digitalization provides the driver for connectivity and interoperability to enhance the value of HwL as it attains scale and more users (Kubli and Ulli-Beer 2016). For example, aggregating systems to the scale of smart cities where "connected intelligence" underlies many aspects of daily life creates increases adoption of HwL behaviors as more people engage with the system (Komninos 2019). The value of peer to peer energy trading among households also increases with users (Morstyn, Farrell et al. 2018). Scale can help with standardization, a prerequisite for network effects. Dominant designs, interoperability protocols, open data protocols, and shared platforms all make adoption easier and more appealing. Regulation and investment in both hard and soft infrastructure are likely necessary to reach the scale needed for network effects to emerge, and to avoid fragmentation of data-enhanced services into private commercial silos (Doblinger, Dowling et al. 2016).

Managing complexity on shared infrastructures

Services for inclusive wellbeing depend on provisioning systems (firms, supply chains) and infrastructures (transport, energy, utilities). Physical infrastructures enabling the HwL scenario apply particularly to digitalization (e.g., universal fast broadband access), sharing economies (e.g. urban pooled vehicle fleets), and renewable electrification (e.g., transmission and distribution networks). Of these three infrastructures, the clean energy transition requires a large expansion of infrastructure with associated material needs (Hertwich 2021, IEA 2021).

In addition to these infrastructure requirements, a cross-cutting theme within the HwL scenario is how these infrastructures are used. In particular, innovation and digitalization combine to enable the balancing and managing of increasingly complex resource flows (e.g., electricity networks) and the effective use of shared infrastructure (e.g., transportation).

First, digitalization enables the integration of high shares of intermittent renewable generators (wind, solar) onto electricity networks, and the balancing of this variable supply with large volumes of distributed storage and demand flexibility resources (EVs, demand response, smart controls, internet of things) (IEA 2017). Digitalization is therefore strongly linked to rapid electrification as a robust strategy for climate change mitigation across all 1.5°C pathways (Rogelj, Shindell et al. 2018). In the LED scenario, electricity provides over 50% of final energy by 2050, with wind and solar contributing around half of total primary energy (Grubler, Wilson et al. 2018).

Second, digitalization can help optimize the resource-efficiency of service provisioning systems using real-time data sensing and analytics to match needs with available resources (e.g., freight and delivery logistics, precision agriculture, digital twin simulations of infrastructure systems, circular economy material flows) (Royal Society 2020). Digitalization also enables more resource-efficient design of products and infrastructures including through the tracing of material contents (e.g., building information modelling and building passports) in the wide context of secondary materials management in a more circular economy (Hedberg and Šipka 2021, Material Economics 2022).

Contexts in which private firms compete to provide services to end-users need to be carefully managed to ensure overall system efficiency. For example, a coordinated and integrated shared and public mobility system optimized to deliver intra-urban mobility requires only a fraction of the vehicles on the road in today's cities (ITF 2017, Moon 2017). But an uncoordinated mosaic of private shared and micro mobility providers, each with bespoke platforms, competing with and cannibalizing high volume public transport routes, has the opposite desired effect (Creutzig, Franzen et al. 2019). Strong governance institutions are needed to coordinate the activity of competing digital providers so as not to undermine public purpose aims.

Quantitative modelling of the High-with-Low scenario

The High-with-Low scenario narrative aims to provide a rich explanation of why and how a resource-efficient future with high levels of wellbeing is achievable. Quantitative interpretation of this narrative using modelling tools will further enrich understanding of policy levers, outcomes, distributional effects, and pathways over time.

Relevant models for High-with-Low analysis will track energy, material, land and other resources converted through service provisioning systems into useful final services. This quantitative step invites modelers to select inputs, parameters, constraints, and model processes that are consistent with the High-with-Low scenario narrative, and that generate change dynamics and outcomes also consistent with the High-with-Low scenario. At their most general, these HwL outcomes must include: (1) decent living standards for all; (2) global warming limited to 1.5°C without large-scale CDR; (3) absolute reductions in the use of resources.[4]

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[4] Global warming outcomes estimated or modelled from long-term carbon budgets are possible in global IAMs with comprehensive coverage of energy and land-use emissions. Other models, including national or sectoral models, should

This leaves considerable interpretative freedom that means HwL scenario modelling will vary widely across models of different scopes, scales, solution algorithms, and purposes. While it is not possible to generate a single set of quantitative parameters for modelling the High-with-Low scenario, here we set out certain guidelines that provide entry points, boundary conditions, and recommendations for supporting modelling efforts.

We start by focusing on the central dynamic of the HwL scenario: rising activity levels for universal DLS, alongside strong structural change[5] towards new forms of service provision (with associated changes in technologies, energy carriers, and infrastructures involved in service provisioning systems). We then provide quantitative insights on the achievement of decent living standards for all (as modelling outputs consistent with the HwL scenario), and finally on peer effects and digital innovations (as modelling processes and inputs consistent with the HwL scenario).

Ensuring High-with-Low modelling is consistent with structural change assumptions and energy intensity improvements

To make transparent the decoupling of resource inputs from service provision outputs in the High-with-Low scenario, we have developed a simple accounting tool called DETRAS. This is based on an extended decomposition analysis of final energy use into activity (A), structure (S), and intensity (I). The framework also explicitly considers the demand for materials and its corresponding energy use with a combined decompositional approach combining materials intensity with energy intensity following the methodology established for the original LED scenario but with improved and revised input/output data. The full DETRAS tool, with accompanying documentation, is available from the authors on request.

Figure 4 illustrates the results for two macro-regions (Global North and Global South) in a revised version of the global LED scenario (Grubler, Wilson et al. 2018). The first “user adjusted” analysis treats end-use sectors and service-related activities as independent from one another. So, for example, urbanization is a scenario driver that affects urban form, mobility needs, dwelling size, and so on, but this is implemented top-down and exogenously on each sector independently. The second "linkages/DLS" analysis includes inter-sectoral linkages as well as explicit consideration of energy needs for meeting decent living standards (DLS). So, for example, more compact urban form and higher density buildings lead to reductions in private motorized mobility, with these linkages being implemented endogenously and horizontally between sectors.

Figure 4 (grey bars) shows that a High-with-Low transition in both global regions is associated with absolute reductions in final energy use between 2020 and 2050. However, the underlying drivers are markedly different, as is made clear by the decomposition of change into the A-S-I components. In the Global North (upper panels), there are only modest increases in activity levels, with decoupling from resource (energy) use predominantly achieved by structural change (-73 EJ) with additional and complementary energy intensity

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aim for consistency with appropriately downscaled or sector-specific 1.5°C pathways, illustrated by the global LED scenario.

[5] Note the alternative economic definition of structural change referring from the transition from primary to secondary to tertiary production (e.g., agriculture to manufacturing to services).

improvements (-47 EJ). In the Global South (lower panels), activity levels rise substantially, particularly as a result of providing universal decent living standards (+49 EJ). The absolute decoupling of final energy use from rising activity levels is achieved roughly half due to structural changes (-79 EJ) and half from energy intensity improvements (-84 EJ).

The overall development pattern of the HwL scenario is therefore one of conditional convergence in which energy services for well-being increase substantially in the Global South catching up to levels maintained in the Global North, while associated resource use tends to converge, combining a contraction in the Global North with relatively modest increases in the Global South.

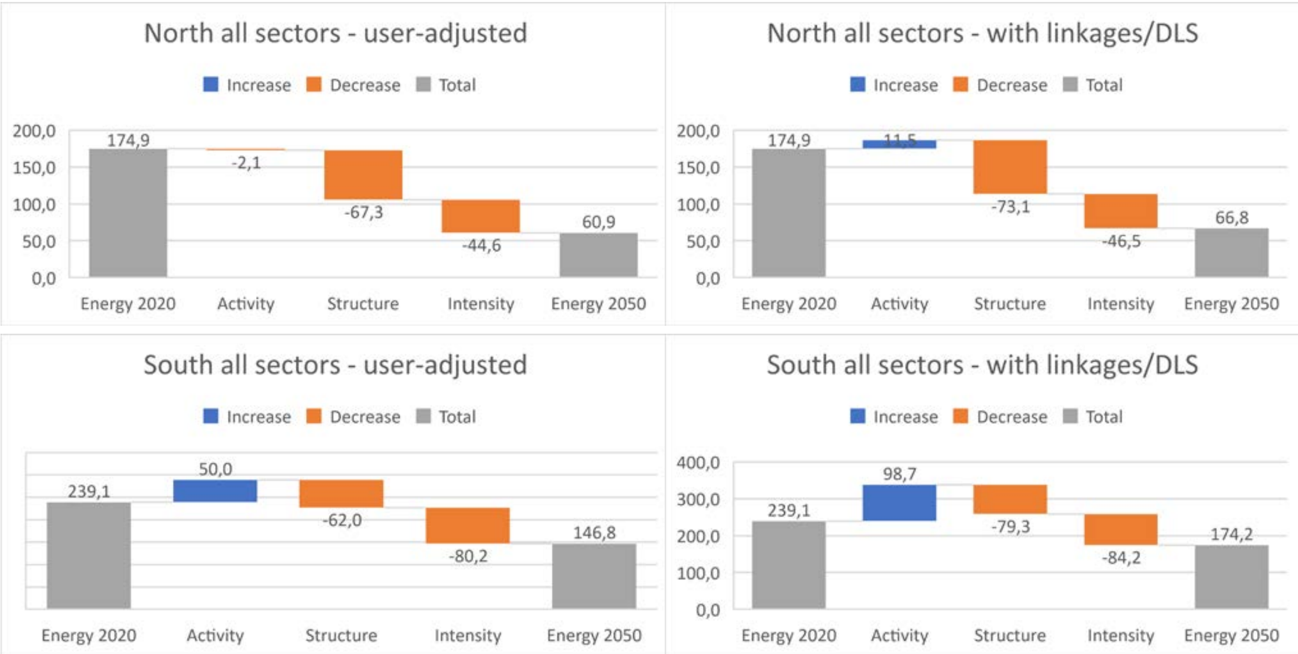

Figure 4. Changes in final energy use from 2020 to 2050 decomposed into activity, structure, and intensity components in a High-with-Low scenario, distinguishing: (1) Global North (upper panels) and Global South (lower panels); (2) user-adjusted global LED scenario (left panels) and inter-sectoral linkages and DLS scenario (right panels). All units in EJ/yr.

For HwL scenario modelling studies with different regional disaggregations (compared to the two region Global North – Global South results shown in Figure 4), we provide the following recommendations:

- Use the DETRAS accounting framework and modify the data with your own region/scenario values for 2020 and 2050.
- Compare the decomposition factors in your scenario to that for global HwL at the aggregate level (all sectors) and *either* provide a descriptive narrative to explain any significant deviations in Activity-Structure-Intensity dynamics (Figure 4) *or* iteratively modify your scenario using the “user-adjusted” feature in the DETRAS tool.
- Repeat the previous step for each end-sector or activity as documented in the DETRAS framework, and revise and document cases of significant departures from the structural change characteristics of the global HwL scenario (Figure 4).

Ensuring High-with-Low modelling is consistent with activity levels and energy requirements to provide decent living standards for all

Modelling the High-with-Low scenario can draw on and benefit from extensive quantitative assessments of decent living standards (DLS). Table 1 makes explicit the underlying assumptions on activity levels and energy intensities assumed for meeting each dimension or component of DLS. Table 2 shows estimated per capita energy gaps to meet DLS for all at a regionally disaggregated level and broken down by each major DLS dimension. These gaps measure the difference between existing levels of energy use for DLS-related goods and services, and levels of energy use required to achieve DLS for all by 2050. This defines a minimum threshold by which energy per capita would need to rise to ensure consistency with the High-with-Low assumptions on DLS.

Note, however, that these DLS-achievement gaps do not assume any major technological or structural changes which may reduce energy use for specific DLS dimensions (e.g., digitalization as an enabler of e-mobility, e-health, e-education). Consequently there may be further potential to narrow these gaps in a dynamic sense through additional changes in service provisioning systems that affect the pace and extent of improvement in energy and material intensities over time.

The data in Table 1 and Table 2 provide benchmarks against which HwL modelling efforts focused on raising living standards can be iteratively tested. Using typical per capita values of alternative service provisioning systems (e.g., from the DETRAS framework) can illustrate the effect of structural change and efficiency improvements on lowering the current energy intensities of DLS. These can be substantial. In addition, alternative service provisioning (e.g. shared mobility as opposed to privately owned vehicles) can also substantially lower service costs and so increase the feasibility and timing of providing DLS for all. For example, a simple assumption of a minimum share of 40% public transport in every region, in comparison to the current split between private and public transit implies a 9% lower energy requirement to provide decent mobility services for all globally (Kikstra, Mastrucci et al. 2021). For the single region of North America (NAM), this difference between simulations with the existing modal split and the higher 40% public transport share is as much as nearly 5 GJ/cap/yr in 2050 (Kikstra, Mastrucci et al. 2021).

The material dimensions to DLS achievement are not currently as well defined, but are being actively explored. One recent study quantified the material stocks (infrastructure requirements) for delivering mobility services in 172 countries in 2021, and assessed empirical relationships against the mobility dimension of decent living, finding diminishing returns to wellbeing above levels of 92 – 207 t/capita of mobility infrastructure (Virág, Wiedenhofer et al. 2022).

Table 1. Activity levels and energy intensities for providing DLS for all. Adapted from: (Kikstra, Mastrucci et al. 2021).

DLS Dimension	Activity	Construction Energy Intensity	Operational Energy Intensity
Nutrition	1653-2066 kcal/cap/day	–	0.8–6.6 MJ/kcal
Cooking	1/hh	0.047 GJ/app	2.2 GJ/app/yr
Cold storage	1/hh	3.8 GJ/app	0.58 GJ/app/yr
Housing	2.1-8.7 cap/hh with 10.1-14.7 m^2 floorspace/cap	3.3 GJ/m^2	–
Thermal comfort	10.1-14.7 m^2 floorspace/cap	1.2 GJ/unit (cooling) 1.2-1.3 GJ/unit (heating)	0.0–88.3 $MJ/m^2/yr$ (cooling) 0.0–1110.8 $MJ/m^2/yr$ (heating)
Water	65 l/cap/day	0.24 KJ/l	2.36 KJ/l
Water heating	30 l/cap/day	-	1.1-3.2 GJ/cap
Sanitation	Provided to all	2.9 GJ/cap	443 MJ/cap/yr
Clothing	2.4 kg/yr (global North) 1.3 kg/yr (global South)	-	129-744 MJ/kg
Footwear	0.9 kg/yr		38-217 MJ/kg
Health	$1024/cap/yr	-	3.03 GJ/$
Education	$1093/student/yr (primary) $2224/student/yr (lower secondary)		
Phone	1/hh	110 MJ/phone	28 MJ/phone/yr
Bigger screen	1/hh	0.99 GJ/television	0.72 GJ/television/yr
Mobility	8527 pkm/cap/yr (rural = 1.24*urban)	0.009 MJ/p.km (bus) 148 GJ/unit (car) 0.035 MJ/p.km (rail) 7.9 GJ/unit (2-3 wheeler)	0.21-2.0 MJ/p.km (bus) 1.0-2.5 MJ/p.km (car) 0.10-0.96 MJ/p.km (rail) 0.54-1.7 MJ/p.km (2/3-wheeler)
Roads		3.8 TJ/km	–

Table 2. Energy gaps for providing five dimensions of DLS for all in eleven world regions. Adapted from: (Kikstra, Mastrucci et al. 2021).

Energy gap in GJ/capita to meet five dimensions of decent living by 2050						
Region	Health	Mobility	Nutrition	Shelter	Socialization	Total Gap
Sub-Saharan Africa (AFR)	3.27	5.79	0.50	0.84	0.97	11.37
Centrally Planned Asia (CPA)	2.25	3.86	0.72	1.31	0.20	8.34
Eastern Europe (EEU)	0.61	2.26	0.00	0.72	0.07	3.66
Former Soviet Union (FSU)	1.48	4.40	0.01	0.00	0.19	6.08
Latin America (LAM)	1.24	3.77	0.35	0.17	0.32	5.85
Middle East & North Africa (MEA)	1.57	5.70	0.12	0.04	0.04	7.47
North America (NAM)	0.00	2.02	0.01	0.00	0.00	2.03
Pacific Islands & Oceania (PAO)	0.00	1.89	0.09	0.00	0.02	2.00
Pacific Asia (PAS)	2.05	3.90	0.39	0.85	0.28	7.47
South Asia (SAS)	3.34	1.96	0.40	1.18	0.54	7.42
Western Europe (WEU)	0.02	2.38	0.00	0.00	0.00	2.40

Ensuring High-with-Low modelling is consistent with innovation processes and technology adoption dynamics

Modelling tools used to explore High-with-Low futures will generally have weak or no representations of the peer effects, network effects, and customization potentials for HwL strategies at the intersection between decent living, innovation, and digitalization (see Appendices for examples of modelling approaches).
Peer effects, network effects, and customization are essential for accelerating improvement and adoption of resource-efficient technologies as they interact to generate non-linear effects.[6] Modelling of High-with-Low futures therefore needs to find ways to more explicitly characterize these dynamics. As examples:

- *Peer effects*. Once stimulated, peer effects can generate non-linear growth in adoption. But they need to be carefully calibrated to determine which stimuli actually produce peer effects and which stimuli have no effects. While this outcome emerges from a largely stochastic process, we can use observed effects, for example that each additional residential solar installation in a neighborhood increases the likelihood of additional adoption by 0.8 percentage points (Bollinger and Gillingham 2012).
- *Network effects*. The possibility of network effects, particularly in urban systems, raises the question of whether we need city-scale objects in modelling simulations of High-with-Low futures. Further needs for disaggregation result from some locations having more absorptive capacity than others because of infrastructure and especially coordination and standards.

[6] For example, with peer effects, a small initial stimulus can catalyze much larger adoption. Network effects can generate increasing returns at higher levels of adoption. Customization can generate entirely new markets. Learning-by-doing can deliver better and lower cost technology to contribute more adequately to expanding access to DLS.

- *Customization*. The potentially important role for local adaptation and customized implementation of generic components implies that more differentiation of HwL strategies will be needed. Customized solutions are highly amenable to learning-by-doing and thus their costs and adoption should be endogenous and dynamic.

First, for each of these modelling challenges, real world data sets are important for calibration. For example, studies of how much more adoption we can expect in locations where peers have already adopted can inform the role of information transmission in agent-based models (Appendix 1). These effects can mediate technology adoption as well as behavioral changes related to energy use (Wolske, Gillingham et al. 2020).

Second, because so many of the dynamics are non-linear we should expect many different possible outcomes and configurations. In other words, modelling results will be less deterministic than without these effects. Scenario and modelling analysis of High-with-Low futures should therefore refocus away from singular, optimal pathways and towards the combinations that give the highest probability of achieving the full potential of HwL options.

Third, for regional and sectoral modelling of the High-with-Low narrative, we suggest two alternative formulations: one along the lines of current supply-focused modelling practice with no peer effects, no network effects, and standardized solutions delivered via centralized business models and infrastructures; and an alternative High-with-Low approach which is end-user focused, distributed, and with customized solutions with peer and network effects. These two contrasting perspectives should then be further described in terms of their innovation and learning effects (leading to cost reductions) as well as their adoption dynamics (e.g., market penetration rates).

Using historical analogues as well as scenario comparisons (e.g., LED vs. SSP2) can serve as a guide to further distinguish the dynamics of supply-focused modelling versus High-with-Low. As an example, cost improvement rates for granular solutions in High-with-Low would typically be up to 20% per doubling of cumulative experience, whereas for large-scale centralized solutions in supply-focused modelling, cost reductions would be much more modest (0-5% per doubling of cumulative experience) due to limited learning and experimentation effects (Sweerts, Detz et al. 2020, Wilson, Grubler et al. 2020).

Similarly, adoption rates for granular, distributed solutions under high peer effects in High-with-Low could achieve 80% replacement of a given capital stock within 10-15 years (e.g., shared mobility schemes). In contrast, adoption dynamics for large-scale centralized solutions would follow more historical trends, ranging between 30-50 years for a 80% replacement in end-use technologies (e.g., fuel cell trucks) and slower still for lumpy capital-intensive upstream supply infrastructures such as hydrogen production and distribution (Grubler, Wilson et al. 2016).

Ensuring High-with-Low modelling is consistent with digitalization impacts on activity and energy use

Digitalization has potentially large but uncertain impacts on energy and material use. Taxonomies distinguish direct, indirect and systemic impacts (Horner, Shehabi et al. 2016). Direct impacts associated with embodied and operational energy used in ICT devices and infrastructures are non-trivial, around ~2-4% of global electricity use (Freitag, Berners-Lee et al. 2022). However they are likely small relative to the indirect impacts of digital services or applications that can either *reduce* energy use (e.g., efficiency, optimization, management, control) or *increase* energy use (e.g., direct or indirect rebound, intensification, novel applications) (Wilson, Kerr et al. 2020). The balance of evidence historically suggests that efficiency gains from digitalization have been more than offset by scale and growth effects resulting from digitally-enabled productivity; consequently digitalization has increased energy demand (Lange, Pohl et al. 2020). The High-with-Low scenario narrative harnesses digitalization for resource-efficient service provision, particularly at the intersection between DLS and innovation, while mitigating and minimizing risks of rebound.

For modelers implementing discrete digitally-enabled innovations for specific end-use services or sectors, recent reviews provide reference points for the potential changes in activity, energy or carbon emissions that can be expected. Figure 5 shows the net effects of a range of end user-oriented digital innovations which include the risk of increased emissions due to inefficient substitutions, induced demand, and rebound effects (Creutzig, Roy et al. 2022). In implementing the High-with-Low scenario, modelers should use effect sizes towards the lower end of these ranges given scenario assumptions that rebound is carefully managed through purposive governance and coordination. In the Appendices, we provide similar data on the effects of digitally-enabled technologies and consumption practices in residential, mobility, and food sectors that are consistent with High-with-Low narrative and outcomes based on recent quantitative syntheses (Wilson, Kerr et al. 2020).

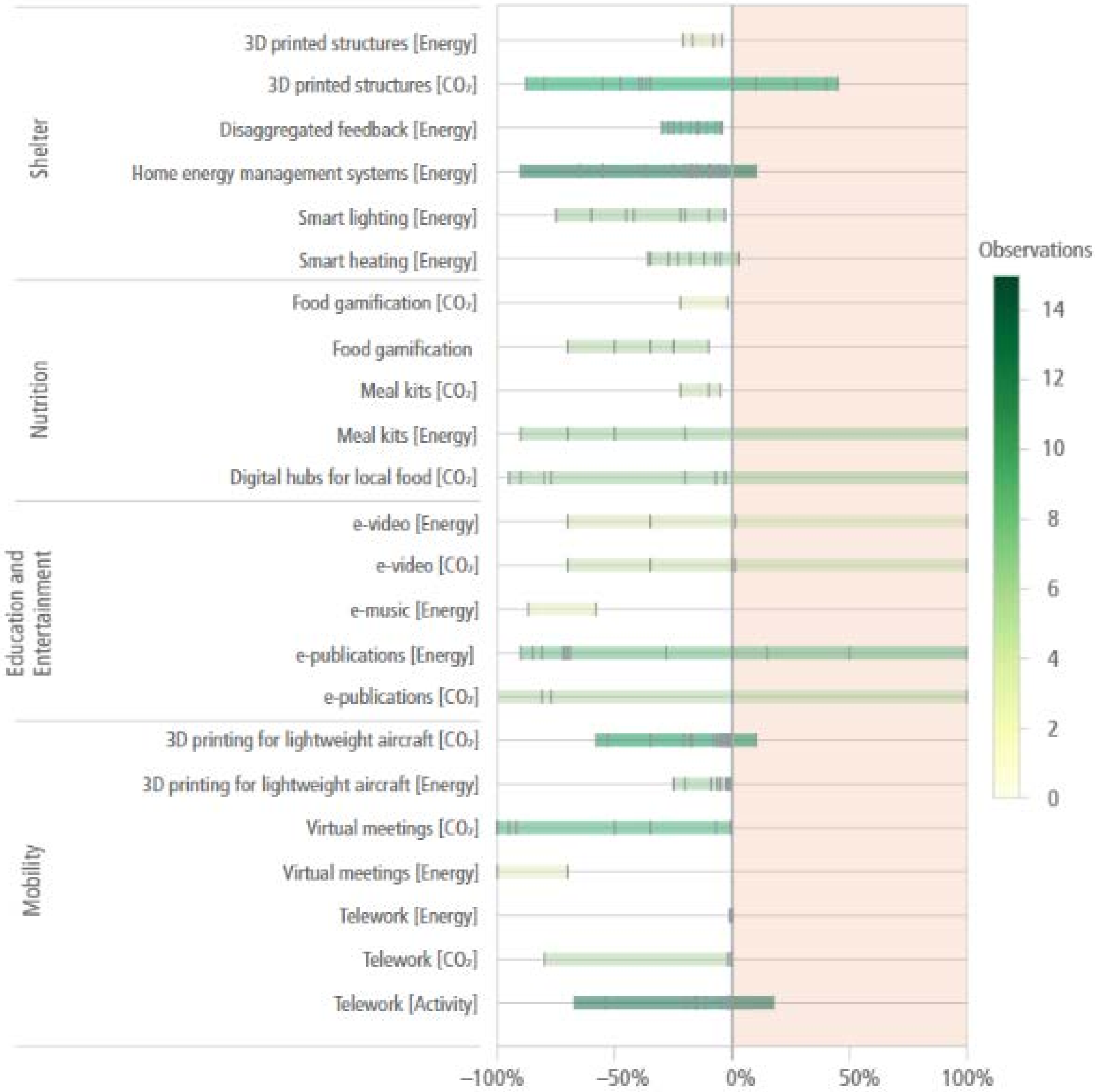

Figure 5. Synthesis of estimates of net changes in CO_2 emissions, energy use and activity levels as an indicator of mitigation potentials from end-user oriented digitalization. Source: Figure 5.12 in Chapter 5 of the Working Group III contribution to the IPCC's sixth assessment report (Creutzig, Roy et al. 2022).

Governance to achieve the High-with-Low scenario

Governance and institutions are integral for High-with-Low futures because each of HwL's central themes - decent living standards, innovation, and digitalization - depend on coordination functions. Based on the HwL dynamics discussed above, here we describe four aspects of HwL governance: shared expectations about direction of change; orienting incentives towards public purpose; infrastructure coordination; policy experimentation. In each case, governance plays an enabling function of corralling a highly distributed program of transformation towards HwL goals. Governance also serves a controlling function in each case to mitigate risks which are pervasive in this emerging area. Managing these risks is likely to be consequential to achieving a transition to HwL. We thus address risks in this section as well as in the concluding discussion below.

Shared expectations about direction of change

At a macro level, governance can establish shared expectations about the direction of change. For the High-with-Low scenario overall, these coordination and regulation needs for each of the three central themes—decent living standards, digitalization, and innovation—need to be integrated into a coherent and synergistic approach to HwL governance. This involves creating expectations, widely shared within and across societies, of a High-with-Low future through a broad mix of policies to support HwL innovation that are comprehensive in scope, and ultimately need to be local in their implementation to reflect heterogeneous adoption contexts. This includes orienting innovation and digitalization toward inclusion and decent living standards by: easing access to technology, including financial and intellectual property; reducing barriers, such as up-front costs; targeting broad affordability; and making disruptive design and production compromises.

Shared expectations can help diffuse successful HwL approaches by reducing risk-aversion in adoption and shifting the balance of considerations towards positively oriented peer-effects. With a supportive institutional environment in place, early adopting peers act as trusted information brokers to support positively self-reinforcing social network diffusion processes for HwL approaches. A real risk to a HwL future is aversion to change; that skepticism about the possibility of transformative change can be self-reinforcing. Governance can play a role in mitigating this risk through a process of developing a societal vision that a HwL future is realistic and probable.

Orienting incentives toward public purpose

On a micro level, governance provides rules and incentives to orient change toward public purpose. Innovative activity, especially via digitalization needs clear direction towards public purpose to ensure it is aligned with decent living outcomes. Absent effective regulation, private service providers will seek to collect, hoard, commoditize, and exploit data about user preferences and behaviors. High-level reports, syntheses, and position papers have detailed the importance of governance for the entwined digitalization and sustainable development agenda (TWI2050 2019, Digitalization for Sustainability (D4S) 2022, Kaack, Donti et al. 2022, Pauliuk, Koslowski et al. 2022). Policies, rules, regulations, norms, and other governance institutions for digital applications can re-orient activity toward HwL outcomes. For example, they can tackle digital exclusion and facilitate universal access to digital skills and infrastructure, regardless of location, income, employment, or age. They can support democratization and participation in the workplace to help transform unsustainable industries and jobs (Pichler, Krenmayr et al. 2021). Where existing distributions are very unequal, redistribution may be required, specifically in the case of very resource-intensive or environmentally damaging services (e.g., private automobility). A particular risk for digitalization in pursuit of HwL outcomes is the potential for substantial rebound effects, as new services become more intensively used. Regulators can moderate rebound to avoid HwL solutions enabling more excessive consumption. For example, they can collect and analyze data on usage patterns and provide incentives for lower usage, or they can encourage re-use of shorter-lived devices and support the development of recycling infrastructure to encourage circularity.

Coordination of infrastructure

Governance is also crucial for coordination of infrastructure, both physical and digital. For example, for decent living standards, a greater degree of coordination and regulation of basic infrastructure will be needed for it to expand rapidly, at least initially. This will require a massive scale-up of public investment alongside spatial planning and design thinking to ensure efficient provisioning systems with low resource footprints (Fisch-Romito 2021). It also includes integrating new forms of private service provision with public infrastructures to ensure overall system performance in meeting human needs. Public authorities and institutions can thus play a role in ensuring interoperability among providers and provisioning systems, including through standard setting. Further, they can co-design the rollout and deployment strategies for products, infrastructure, markets, business models, and regulations.

A key risk to mitigate is industry concentration, which can easily accrue via network effects in both hard and soft infrastructures. In particular, digitalization's winner-takes-all networks and platforms lead to market dominance. However these monopolistic practices give cities, regulators and governments the opportunity to enforce a 'social compact' or 'social license to operate', i.e., continued market access in exchange for open data, public benefits, tax contributions to support the education and infrastructure on which digital services depend, and space for a wide variety of actors including local entrepreneurs, civic groups, and public organizations to remain actively involved in developing, trialling, rolling out, and competing to provide digital services across the different dimensions of decent living. These activities extend to fostering competition and avoiding risks of monopolies by stimulating novelty, entrepreneurship, and new services while limiting firm creation of barriers, rents, and monopolistic or oligopolistic practices and pricing. This could, for example, include ensuring digital citizenship standards that empower users with data rights and avoid predatory data harvesting that undermines agency and social institutions.

In some cases, these infrastructures create natural monopolies in which end-user and consumer rights protection is paramount, not just for pricing but also for access and maintaining choice. In others, competition can be supported alongside accessibility of private individual and community service providers to the market. Allowing for a range of new entrants therefore becomes an important governance function. Well designed and implemented governance can enhance standardization and interoperability including through new business models that can make use of shared platforms, while remaining open themselves to complementary innovations.

Policy experimentation

A key risk with the strong governance institutions and approaches argued for to deliver HwL outcomes is that policies become too strong, and thus develop rigidity and self-reinforcing characteristics. This can be problematic in a transition environment characterized by change and uncertainty. An approach to policy design that embraces experimentation is crucial for accommodating the inherent uncertainty in how these systems evolve at scale. This involves iterating through policy experimentation, innovation, and diffusion by using supportive rules, subsidies, taxes that can be introduced and evaluated to identify successful policy models. Standardization of high performing policies can be transferred to other jurisdictions, and then adapted for the idiosyncrasies of local context. This is not only necessary for a HwL transition, it is also highly feasible; policy experimentation would take full advantage of the flexibility that the typical granularity in HwL approaches provides and the natural experiments that heterogeneity in local context supports.

Concluding discussion: feasibility of the High-with-Low scenario

Feasibility, risk, and speed in High-with-Low

In this final discussion we zoom out from the central themes, cross-cutting linkages, governance challenges, and model implementation approaches of the High-with-Low scenario to consider its feasibility, risk, and speed in absolute terms and in relation to alternative visions of a sustainable future.

The **feasibility** of a High-with-Low development pathway evidently depends on the evaluation criteria used, as well as subjective norms and values. We consider our High-with-Low scenario to be feasible for three reasons. First, it is in line with universally accepted principles of development and values such as those enshrined in the SDGs.

Second, there is enormous unexploited potential to improve on current systems of service provision which are highly inefficient. Current systems at best deliver some 15% of primary resource inputs as useable services (TWI2050 2020). Step-change improvements are available in the efficiency of service delivery through new technologies, practices, business models, and form of market organization (e.g., service, sharing, or circular economies).

Third, although our High-with-Low scenario requires transformational change, it also offers numerous opportunities for new activities, products and services, and hence jobs and economic opportunity. By lowering absolute resource use in the High-with-Low scenario, the portfolio of solutions is more diversified, benefits are more widely distributed, and more granular solutions enable faster experimentation, testing and improvements. This mitigates against implementation risks in contrast to pathways relying heavily on a few large-scale centralized solutions like nuclear power or geoengineering-scale carbon capture and storage.

However, as noted above, successful roll-out of High-with-Low strategies depends on effective governance across technology development, business model, market design and regulatory dimensions, all of which are subject to uncertainties and political economic pushback from incumbent interests.

The ambition of the Paris Agreement and UN SDGs means any implementation pathway will be transformative and strongly discontinuous from historical trends. The feasibility of alternative pathways is therefore relative as well as absolute. We consider our High-with-Low scenario to be more feasible than alternative pathways that limit warming to 1.5 °C but with significantly higher resource use and reliance on large-scale, unproven technologies like carbon capture, storage, utilization, and removal (Fuss, Lamb et al. 2018). These include pathways in the 'shared socioeconomic pathways' (SSP) framework, widely used in IPCC assessments to characterize the uncertainty space for future emissions, but at (much) higher levels of energy demand (Scott, Smith et al. 2022).

The High-with-Low development pathway sees a significant decoupling of energy inputs from service provision outputs. A common counter-argument is that projected rates of decoupling far exceed historical precedent so are assumed to be infeasible (Semieniuk, Taylor et al. 2021). This argument is misleading for two reasons.

First, the empirical basis of historical energy intensity improvements is almost exclusively limited to economic indicators (energy use per unit of economic output like GDP) that typically improve by rates of 1-2 %/year. These are ill-suited for comparison with physical indicators (energy use per unit of physical service output like passenger-kms of mobility, lumens of light, etc.) that typically improve by 3-7 %/year. This difference is due to learning and cost reductions in end-use services (Nordhaus 1997, Fouquet 2010, Fouquet 2014). As the price of energy services falls rapidly, a dollar of input costs affords ever larger volumes of service. Conversely, using input prices and their aggregates like GDP to calculate economic energy intensity indicators yields lower rates of intensity improvement.

Second, intensity improvements historically have predominantly been achieved via technological efficiency improvements (more fuel-efficient vehicles, higher-efficiency light bulbs, etc.). Structural effects such as changes in modal splits or substitution of analogue by digital consumer goods have had either negligible or countervailing effects (e.g., shift from buses to private cars). Future decoupling of resource use from service provision can therefore be dramatically accelerated with associated structural change. However, this will not emerge endogenously unless powerful lock-in constraints including vested interests are overcome (Schaffartzik, Pichler et al. 2021).

Our High-with-Low development pathway also has several advantages over other pathways in relation to possible **speeds of transition.** First, as a general rule, smaller-scale, modular, distributed, and less capital-intensive solutions (‘granular’) diffuse faster than capital-intensive and infrastructure-intensive large-scale centralized (‘lumpy’) solutions (Wilson, Grubler et al. 2020). Second, people can change faster than infrastructures. Behavioral changes under appropriate incentives can be comparatively fast relative to large-scale technological infrastructures that turn over slowly (Grubler, Wilson et al. 2016). By relying more on distributed, people-centered changes, the High-with-Low scenario can achieve transitions over decadal time scales, compared to alternative pathways with centralized 'lumpy' solutions that do not leverage behavioral changes and unfold over much longer timescales (50-70 years).

Next steps for High-with-Low

The HwL narrative and its guiding decompositional quantification within the DETRAS framework aim to support quantitative scenario modelling activities within the EDITS[7] community and beyond. These modelling

[7] The Energy Demand changes Induced by Technological and Social innovations (EDITS) network is an initiative coordinated by the Research Institute of Innovative Technology for the Earth (RITE) and International Institute for Applied Systems Analysis (IIASA), and funded by the Ministry of Economy, Trade, and Industry (METI), Japan

efforts range in both scale (from national to global models) as well as in sectoral detail and scope (from sector-specific modelling such as in transport all the way to full coverage of all salient human activities). As such we intend this working paper on the HwL scenario narrative to serve as a “living document” that should be revisited again at a later stage once experience with HwL modelling accumulates and novel needs for deepening and/or widening the HwL narrative become clearer. Several potential areas for further work have also been identified in the iterative process that led to this current HwL scenario working paper. We list a few here to suggest possible areas of further research and conceptualization:

- More explicit consideration of food use and production and its associated environmental footprint (land use, water, biodiversity).
- More explicit consideration of distributional aspects including not only consideration of well-being “floors” but also starting to engage in a wider discussion on the non-linear relationships between levels of service provision and wellbeing under the sufficiency rubric, including possible wellbeing dis-benefits of overconsumption.
- Extending the HwL narrative and DETRAS quantification to differentiate between stock and flow variables, particularly important for materials and for the determinants of wellbeing (human, social, knowledge and manufactured capital and infrastructures).
- Developing richer narratives around governance and market organization forms and associated institutional settings that reflect both historical and social path dependency as well as invite thinking about possible innovations and their resulting impacts.

Appendices

Modelling approaches to capture peer effects, network effects, and standardisation

First, peer effects are a prominent feature of agent-based modelling tools that allow for social interactions and information exchange through social networks (Rai and Robinson 2015, Zhuge, Yu et al. 2020). However, they rarely feature in sectoral, systems, or process-based integrated assessment modelling used to project long-term transformation pathways such as High-with-Low. Recent global studies have parameterized social influence within global integrated assessment models to explore the effect of social learning on the adoption of low-carbon technologies like electric vehicles (McCollum, Wilson et al. 2018). Peer effects and technological learning have a mutually reinforcing effect on cost reductions and performance improvements that accelerate change (Edelenbosch, McCollum et al. 2018). However, these attempts to endogenize peer effects are the exception not the rule.

Second, distinct from learning effects, network effects stimulate adoption as the value of innovations increases with the number of users. For example, a discrete-choice model of electric vehicle adoption shows that positive feedback effects support further adoption as charging infrastructure expands (Li, Tong et al. 2017). Network effects are included in modelling tools only in the sense of enabling infrastructure such as electricity networks (e.g., aggregation of disparate loads which leads to higher load factors and more efficient infrastructure utilization). But these are not simulated at urban scales, for example, in which infrastructure for shared mobility could expand mobility choices.

Third, the opportunities created by granular LED technologies for customization and learning-by-doing across different DLS niches are not captured in modelling tools. Technologies tend to be highly aggregated and uniformly represented across adoption contexts (e.g., in cost, performance, energy system interlinkages). The closest approximations to local distinct niches are from input prices (e.g. fuels) that can vary regionally.

Quantitative impact of digitalization on residential energy service provision

Figure 6 shows the effects on activity, energy or carbon outcome indicators from the adoption of digitally-enabled technologies and practices in the home. These are all examples consistent with the High-with-Low narrative and its emphasis on digitalization as a central theme. Similar quantitative syntheses are available for mobility and food-related innovations from the same source (Wilson, Kerr et al. 2020).

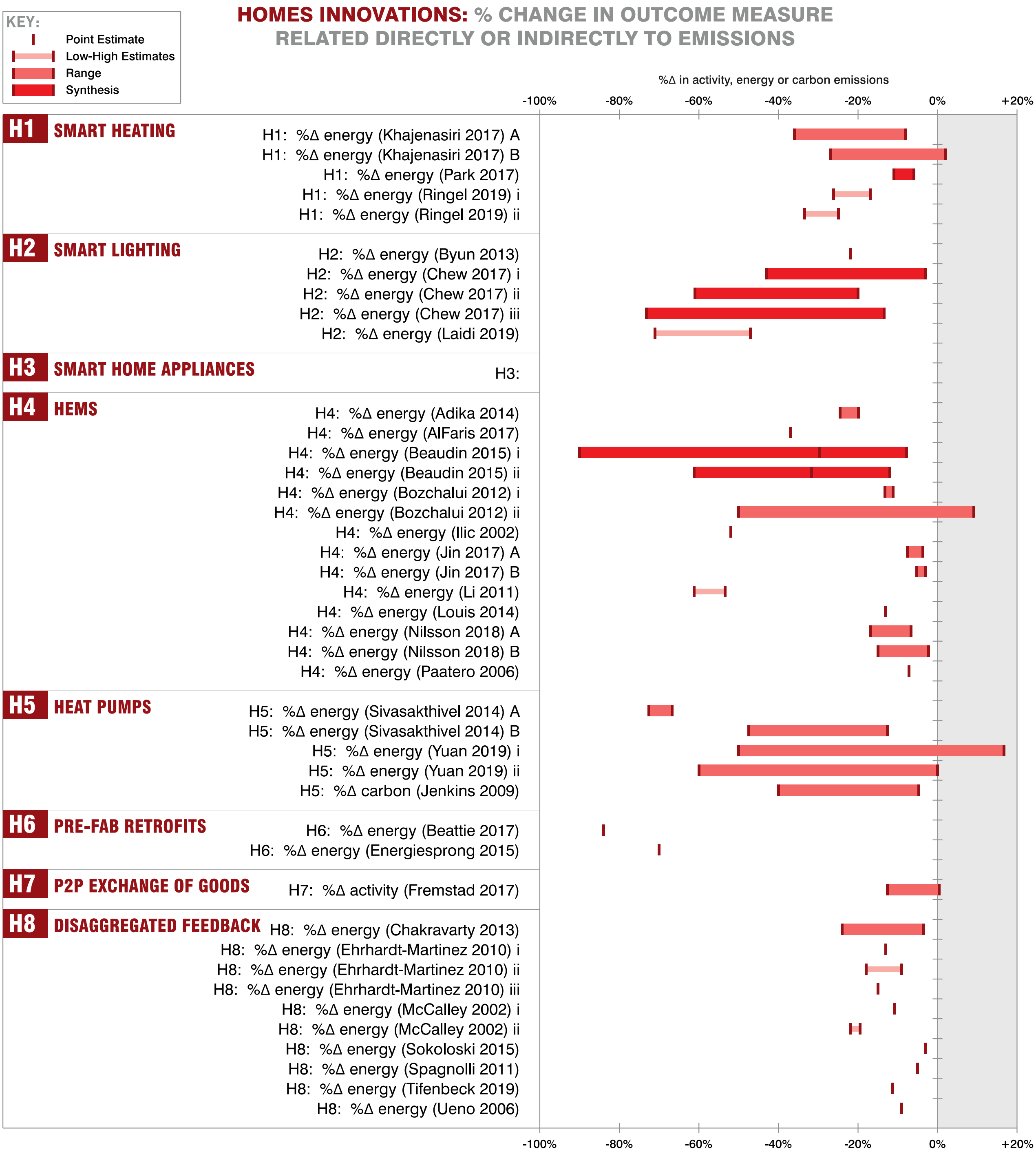

Figure 6. Synthesis of estimates of net changes in CO_2 emissions, energy use and activity levels as an indicator of mitigation potentials from digitally-enabled LED technologies in the home. Note: similar estimates are available for digital mobility and food innovations. Source: (Wilson, Kerr et al. 2020).

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