

1 **A framework for modelling consumption-based energy demand and emission pathways**

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9 ABSTRACT Energy demand in global climate scenarios is typically derived for sectors – such as
10 buildings, transportation, and industry – rather than from underlying services that could drive
11 energy use in all sectors. This limits the potential to model household consumption and lifestyles
12 as mitigation options through their impact on economy-wide energy demand. We present a
13 framework to estimate the economy-wide energy requirements and carbon emissions associated
14 with future household consumption, by linking Industrial Ecology tools and Integrated Assessment
15 Modelling (IAM). We apply the framework to assess final energy and emission pathways for
16 meeting three essential and energy-intensive dimensions of basic well-being in India: food,
17 housing and mobility. We show, for example, that nutrition-enhancing dietary changes can reduce
18 emissions by a similar amount as meeting future basic mobility in Indian cities with public
19 transportation. The relative impact of energy demand reduction measures compared to
20 decarbonization differs across these services, with housing having the lowest and food the highest.
21 This framework provides complementary insights to those obtained from IAM by considering a

22 broader set of consumption and well-being related interventions, and illustrating trade-offs
23 between demand and supply-side options in climate stabilization scenarios.

24 **1. Introduction**

25 Meeting the goals of the Paris climate agreement will involve greenhouse gas (GHG) emission
26 reductions through a portfolio of mitigation measures, including lowering demand and resource
27 intensity, and decarbonizing the energy supply sector^{1,2}. Global scenarios of climate stabilization,
28 such as those developed using Integrated Assessment Models (IAM), place greater emphasis on
29 supply side transformations^{3,4}, including the energy system and land-use, than they do on
30 demand-side changes, with few exceptions^{5,6}. Demand-side measures typically focus on direct
31 energy services in sectors (e.g. buildings, industry and transport) more than they do on
32 consumption and lifestyle changes^{4,7} that drive energy demand indirectly through their material
33 use. For example, changes in household demand for mobility and housing can have differing
34 impacts on energy demand depending on their material requirements for manufacturing vehicles
35 and constructing buildings, respectively. These indirect impacts are mostly overlooked by IAM.
36 As a result, global scenarios of climate mitigation are limited in their ability to represent
37 household consumption and lifestyle change through their use of materials and economy-wide
38 energy demand^{5,8,9}.

39 Recent research suggests that the linkage of Industrial Ecology (IE) tools to IAMs can strengthen
40 the representation of the supply chains, material cycles and household consumption patterns in
41 climate change stabilization scenarios^{10,11}. Previous efforts to integrate IE and energy systems
42 scenarios assess the material implications of energy supply transformations to meet climate
43 targets¹¹⁻¹³. IE methods, such as Life Cycle Assessment (LCA) and Environmentally Extended

44 Input-Output (EEIO) analysis, connect production and consumption activities to their associated
45 energy and resource use by mapping supply chains. Integrating IE methods and energy scenarios
46 can enable an assessment of the trade-offs and synergies between production, consumption,
47 material requirements and energy use of different climate change mitigation options.

48 IE studies that evaluate demand-side emission reduction potential offer a range of flexibility to
49 represent future energy system transformations. Traditional LCA methods were designed to
50 assess specific products and processes. As a result, they tend to be static in time and oriented to a
51 micro-scale^{8,14} More recently, several studies assess future environmental changes across a
52 broader scope of economic activity. However, often LCA studies neglect future changes in the
53 energy system¹⁵⁻¹⁷. Other recent hybrid LCA-IO studies do include impacts of energy system
54 changes, but their main scope of analysis is limited to the electricity sector¹⁸ or specific end-use
55 services, such as transport¹⁹, efficient lighting²⁰, and energy management systems²¹. On the
56 other hand, EEIO analysis has been widely used to assess historical indirect energy and
57 emissions from sectors based on consumption-based accounting principles²²⁻²⁷. Recent studies
58 attempt to project EEIO models into the future based on a given set of technology and climate
59 scenarios and simplified projections of changes in household final demand structure^{28,29}. This
60 dependence on specific, and most likely different, scenarios of energy system transformations
61 makes these studies difficult to compare to each other or extend to other demand categories and
62 IAM scenarios of energy system transformation.

63 Despite these efforts, studies that project economy-wide household service-driven energy and
64 emissions pathways are largely missing. In a previous work³⁰, we proposed the Service-Driven
65 Energy Accounting model (SEAM) to calculate products' embodied final energy demand, which
66 aggregates relevant direct energy demand in all the traditional sectors involved in the product

67 supply chain. In this paper, we extend the SEAM framework to develop emissions pathways for
68 household services by combining estimates of final embodied energy demand and emissions of
69 products with IAM scenarios of decarbonization. This framework enables a comparison of the
70 mitigation potential of well-being driven interventions to reduce consumption across different
71 product groups and at different points in the supply chain to the more traditional demand
72 reduction and supply-side options in the energy system obtained from IAMs. This approach of
73 integrating consumption with IE and IAM also allows us to differentiate energy and emissions
74 associated with building new infrastructure and that associated with providing services over
75 existing infrastructure. For instance, one could compare the mitigation potential of, such as
76 behavioral change in building space cooling compared to electrification in the mobility sector.

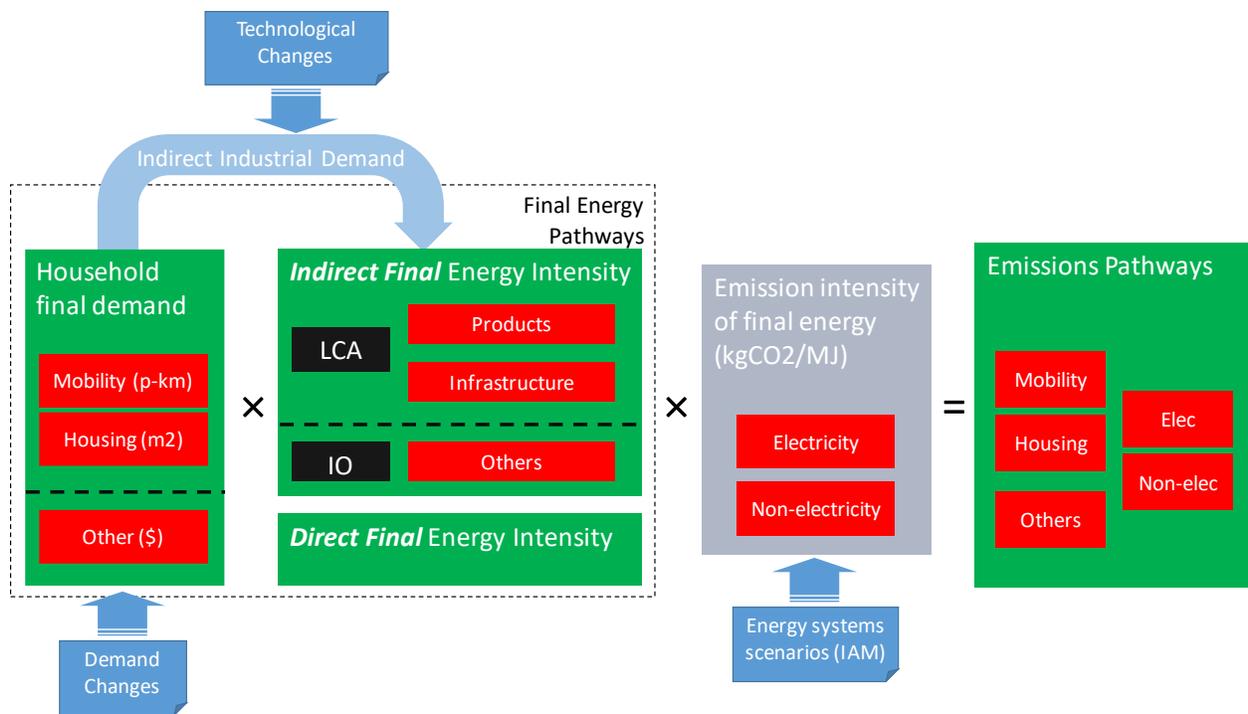
77 We apply this model to illustrate energy and emissions pathways for bridging gaps in three key
78 services of “decent living standards” (DLS) in India ³¹: housing, mobility, and food. We generate
79 scenarios to bridge existing service gaps, including building the necessary underlying
80 infrastructure. We explicitly model influences of behavioral and technological changes on energy
81 demand on the one hand, and future changes in energy supply on the emissions pathways, on the
82 other, to illustrate their relative contribution to decarbonization of basic needs.

83 **2. Materials and methods**

84 Our generic framework includes three steps (Fig.1). First, we estimate the demand level for
85 residential (square-meters of floor surface per housing type), mobility (p-km per transportation
86 mode) and other services such as food (expenditure level) according to previously identified
87 standards³²⁻³⁴. Second, we calculate direct and indirect final energy demand associated with
88 materials and services. For this, we use IE tools, as appropriate, to estimate the indirect energy

89 intensities per service unit: LCA for services with easily definable material requirements, such as
 90 buildings and mobility; and EEIO analysis for the remaining services whose material use is more
 91 diffused through the economy. We then build scenarios which model current practices as well as
 92 low-carbon technologies, consider their future penetration and include material efficiency
 93 improvements. We estimate the total final energy requirements by multiplying the demand of the
 94 service in each scenario by the respective energy intensities. Third, we calculate emissions
 95 pathways under different scenarios of climate policy, including a reference and climate
 96 stabilization at 1.5°C, using carbon intensities of fuels from IAM scenarios.

97 The following sections describe the generic LCA and EEIO methods we developed to estimate
 98 the indirect final energy intensities of services, the exemplary application to DLS scenarios, and
 99 the three modelled end-use sectors (housing, mobility, and food).



100

101 **Figure 1.** Overview of the methods for final energy and emissions pathways.

102 ***2.1. Energy intensities calculation***

103 *LCA*

104 We use process-based LCA to link services to their indirect energy requirements and develop
105 energy demand pathways in final energy terms. This differs from traditional LCA, where final
106 energy is disregarded in favor of primary energy for assessing depletion of energy resources. To
107 our best knowledge, only two studies in literature used a similar approach and estimated energy
108 coefficients from LCA for assessing power sector scenarios^{8,35}. Our application differs in that it
109 focuses on end-use services and linkages with induced final energy demand.

110 We derive final energy demand by calculating ratios of final to primary energy for specific
111 products or processes. As first approximation, we assume that the difference between primary
112 and final energy is the conversion and delivery losses for electricity production and distribution
113 respectively, and that final energy equals primary energy (that is, conversion losses are assumed
114 negligible) for energy carriers other than electricity³⁶. Products' and processes' relative final
115 energy intensity differ from their relative primary energy intensity based on the share of
116 electricity – and in turn its efficiency of conversion.

117 The final electricity embodied in each product of interest is estimated by using the technology
118 matrix³⁷, which maps inflows and outflows of commodities from processes. The activities
119 supplying electricity for end uses are filtered along the supply chain via the technology matrix
120 and the associated electricity use summed up (see Supplementary Information). We then run the
121 impact assessment and use the indicator Cumulative Energy Demand (CED)³⁸ to calculate
122 embodied primary energy, which as explained above, for non-electricity products is assumed to
123 be the same as final energy use. The embodied final energy related to other fuels is calculated as

124 the difference between total CED and CED of the electricity supply activities associated with a
125 given product. We finally obtain two coefficients to customize results to the local context for
126 each product: the electricity share of final energy; and the ratio of final to primary energy (see
127 Supplementary Information). We use Brightway2³⁹ to process data from the database
128 Ecoinvent⁴⁰ (v3.3 cut-off).

129

130 *EEIO analysis*

131 We use the standard EEIO equations⁴¹ to calculate the indirect final energy intensities of 200
132 products of EXIOBASE3—a widely used environmentally extended global multi-regional input-
133 output (EE-GMRIO) database. The key difference with previous studies that use EXIOBASE is
134 that we employ a final energy extension extracted from net energy use (NEU) accounts
135 specifically developed for this analysis. NEU refers to the end use energy of energy products
136 minus exports plus all energy losses (i.e. during extraction, transformation, storage and
137 distribution)⁴². The NEU accounts built for this paper are largely based on the approach used in
138 Stadler et al.⁴³ and documented in Usubiaga-Liaño et al.⁴⁴ (see Supplementary Information). In
139 short, the extended energy balances of the International Energy Agency^{45,46} are first transformed
140 from the territory to the residence principle to resolve accounting differences (see Usubiaga et
141 al.⁴⁷ for more details). From the resulting dataset we calculate the energy product-specific NEU
142 and only allocate the final energy consumption to EXIOBASE products and final consumers
143 using the same allocation approach as in Stadler et al.⁴³, which results in a final energy use
144 extension. Then, indirect final energy intensities are derived from this extension using the
145 standard demand-pull IO model. The intensities by EXIOBASE product are then mapped to

146 matching COICOP (Classification of Individual Consumption According to Purpose) categories
147 by the approach given in Min and Rao⁴⁸. For the aggregate food energy intensity, we weight-
148 average the final energy intensities by COICOP category with the monetary share of different
149 food items in the diets considered in the DLS scenarios. While the intensities for each of
150 COICOP categories are assumed constant over time (i.e. no changes in production processes),
151 the aggregate intensities change over time due to the changes in diet composition in different
152 scenarios.

153 *2.2. Application to DLS scenarios*

154 Previous work has focused on identifying a set of components defining DLS³¹. Here, we
155 illustrate the merits of the proposed methods by developing final energy and emissions pathways
156 for three key end-use services in DLS scenarios: housing, mobility and food. Energy
157 requirements are divided in two components: the operational energy associated with the
158 provision of goods and services (including direct energy for housing and mobility, and indirect
159 energy for food production); and the construction energy necessary to build the underlying
160 infrastructure (housing construction, public transport infrastructure, and vehicles production).
161 We do not include other food-related energy used directly in households such as cooking or
162 refrigeration. India provides a remarkable case study for the important gaps in access to decent
163 living and opportunities for limiting the energy and GHG emissions required to fill such gaps.

164 We present two demand scenarios for 2050, where DLS gaps are filled by 2030, in accordance
165 with SDGs targets⁴⁹. These gaps include access to decent housing, motorized transportation and
166 adequate nutrition (see below). In the reference (REF) scenario, requirements are fulfilled with
167 current prevailing development strategies and technologies. The low-carbon technology (LCT)

168 scenario includes exemplary emissions-saving development strategies, such as energy-efficient
169 design for buildings, public transportation and diet changes. A variant of the LCT scenario for
170 mobility (LCT*) evaluates the complete electrification of public transportation by 2030.

171 In a second step, the scenarios above are further developed by incorporating potential changes
172 in energy supply system that lead to a decrease of emission intensities for supplying electricity
173 and other non-electric fuels (separately for industry and transportation) from two representative
174 climate policy scenarios. One is no energy policy scenario (PS1), where we assume no policy
175 changes from status quo, and thus the average emission intensities of India in 2015 are kept
176 constant until 2050 (0.235 kgCO₂/MJ for electricity, 0.055 kgCO₂/MJ for non-electric fuels in
177 industry, 0.072 kgCO₂/MJ for non-electric fuels in transportation). The other (PS2) is an
178 ambitious policy scenario, which represents the efforts needed to have 66% chance of limiting
179 the global temperature increase to under 1.5°C in 2100⁵⁰ (emission intensities in 2050 are -0.002
180 kgCO₂/MJ for electricity, 0.007 kgCO₂/MJ for non-electric fuels in industry, 0.044 kgCO₂/MJ
181 for non-electric fuels in transportation). We include non-energy emissions for cement in housing
182 construction and methane in food production (see Supplementary Information for more details on
183 emissions intensities). From this, we can separately investigate the relative contribution of
184 demand- and supply-side policies in reducing emissions growth.

185 *Housing*

186 The DLS for housing include minimum floor surface (10 m² per person, minimum 30 m² up to
187 3 persons), permanent construction materials and a suitable level of thermal comfort^{31,33}. We
188 represent rural and urban housing by a single-story and a multi-story archetype respectively,
189 reflecting prevailing construction practices⁵¹⁻⁵⁵, and focus on construction and space cooling-

190 heating only (appliances and other end uses are not considered). We rely on previous studies for
191 the estimation of energy requirements for space cooling and heating under the five different
192 climatic zones in India (see Supplementary Information). In the REF scenario, we keep the
193 characteristics of new housing unaltered over time. In the LCT scenario, we incorporate energy-
194 efficient building design that reduce both construction and operational energy requirements⁵¹ and
195 material efficiency improvements for steel and other construction materials.

196 The extension of the housing stock is estimated for every time step based on the housing
197 demand, driven by population growth and the housing gap. Currently, India has a housing gap of
198 50 million units⁵⁶, due to poor construction quality, overcrowding and homeless population. We
199 assume universal access to decent homes by 2030 according to SDG11 (Sustainable cities and
200 communities). The yearly building turnover rate is fixed at 2% of the total stock, considering a
201 service life of 50 years^{55,57,58}.

202 *Mobility*

203 Normative requirements for mobility include access to motorized public and private
204 transportation. In previous work, we adopt a minimum mobility requirement of 10,000 p-km,
205 triangulated from a number of data points on minimum travel distance in dense industrialized
206 countries^{32,59}. In the REF scenario, we keep transportation mode shares constant at present levels.
207 In the LCT scenario, all future incremental mobility demand in cities is met by public transport,
208 which has lower energy intensity per p-km and congestion reduction benefits⁶⁰, while the mode
209 shares are maintained constant in rural areas. The fuel mix of the fleet is considered as constant
210 over time in both scenarios. The construction energy for public transportation infrastructure is

211 estimated based on previous studies⁶¹, construction of roads is not included. We use a stock
212 model for LDVs production activities over time (see Supplementary Information).

213 *Food*

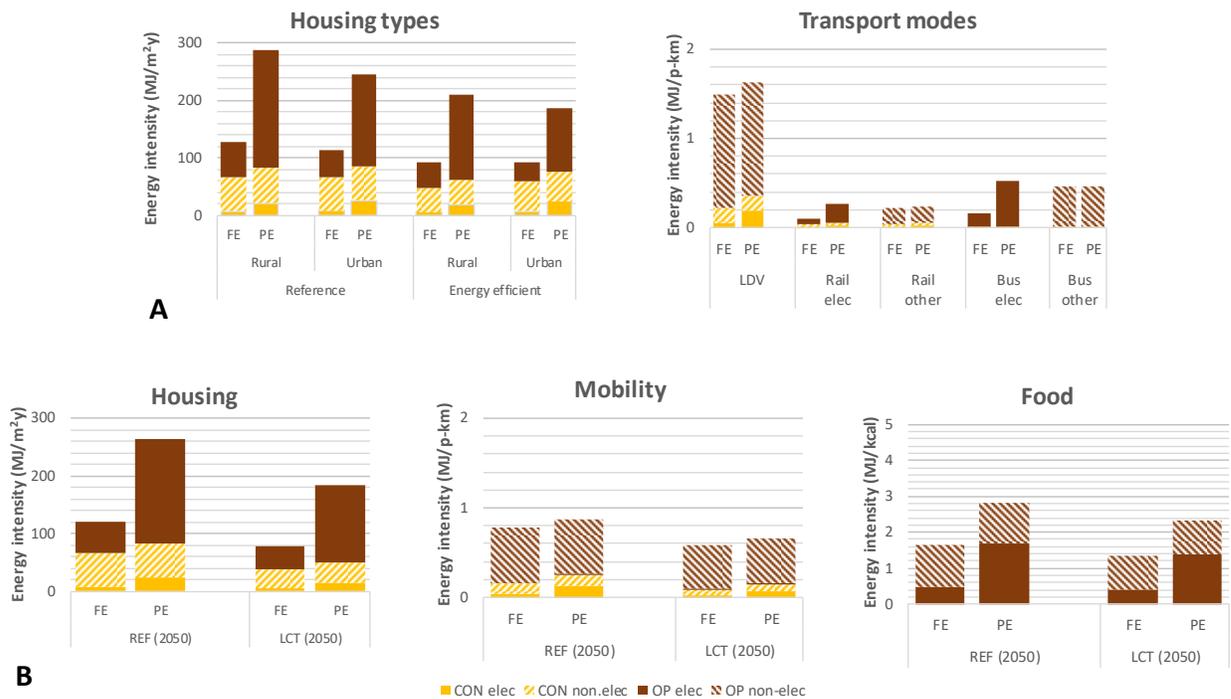
214 For food, in the REF scenario, nutritional requirements (represented by dietary reference
215 intakes (DRI)) are met in 2030 based on present diets⁶². The LCT scenario represents emissions-
216 minimizing diets that also meet the DRIs, but only by 2050, to allow for the time associated with
217 the implied dietary shifts. Note that the calorie requirement is constant over time, but its
218 composition varies with the scenarios. In particular, the calorie share of methane-intensive rice
219 reduces from 31% in REF to 5.6% in LCT due to its substitution by other grains such as wheat,
220 potato, corn, bajra, etc.

221 **3. Results and Discussion**

222 This analysis enables a comparison of the embodied energy intensities of basic *services* enjoyed
223 by households in an economy, independent of their economic value and energy supply. We discuss
224 the features and benefits of these types of results in three steps: we first compare these energy
225 intensities to conventional approaches that present primary energy intensities; we then compare
226 the construction and operational energy requirements of these services; lastly, we discuss the
227 relative mitigation potential across services and across the energy supply chain (i.e. demand
228 reduction vs decarbonization). We discuss the empirical findings as well, but primarily as a vehicle
229 to illustrate the methodological contribution.

230 ***3.1. Final vs primary energy intensities***

231 Figure 2 compares the final and primary energy intensities for different housing types (new
 232 construction) and transport modes (panel A) and the averages for all the services in both REF
 233 and LCT scenarios in 2050 with no changes in the current energy system (panel B). We separate
 234 the energy associated with electricity and the rest, in order to illustrate their difference in
 235 decarbonization potential.



236

237 **Figure 2.** Panel A - Final energy (FE) and primary energy (PE) intensities of housing types
 238 (new construction) and transport modes. Panel B - Average FE and PE for housing, mobility and
 239 food in India in the reference (REF) and low-carbon technologies (LCT) scenarios in 2050 with
 240 no changes in the current energy system (panel B). Breakdown of FE and PE shown into
 241 construction (CON) and operation (OP) energy, and attributable to electricity use (elec) and other
 242 fuels (non.elec). See Supplementary Information for more details.

243 Due to the high conversion losses in electricity production, the energy demand when portrayed
244 in terms of primary energy shows a misleading dominance of use. Electricity use for cooling, for
245 instance, comprises less than half of the life-cycle energy demand for buildings, but in primary
246 energy terms its contribution is around two-thirds. This share is even less in urban areas,
247 because multi-storey buildings are more efficient per unit of floorspace. Viewing energy demand
248 in final energy terms better informs the leverage efficiency improvements in operation can have
249 on overall energy use relative to upstream changes in building construction (e.g. cement
250 production) or electricity production. Furthermore, with this information one can assess the
251 impact on energy demand from just the structure of growth (e.g. urbanization), in this case,
252 through its effect on building stock. For mobility, electricity comprises a greater share of
253 construction energy demand (25 percent) than in buildings (9-12 percent) because of the
254 electricity intensity of steel, which in turn comprises a higher share of materials in vehicles than
255 in buildings. For food, a relatively small share of electricity in overall final energy shows that
256 efficiency improvements in typical electricity consumption along the supply chain of food (e.g.
257 storage, refrigeration, packaging) will have a limited role under the current practice. The relative
258 proportion between reductions in final energy terms and in primary energy terms, for a specific
259 service, is therefore influenced considerably by the share of electricity versus other fuels for the
260 adopted measures.

261 Having service-driven energy intensities also enables complementary scenario analysis, in that
262 the relative effects of interventions at different points in the supply chain can be compared
263 (Figure 2-B). For instance, a comparison of the average energy intensities of services in the REF
264 and LCT scenarios in 2050 reveals that the relative extent of energy demand reduction from
265 different interventions in the three services: 35 percent for housing from improved design and

266 low-embodied energy materials; 24 percent for mobility from deeper penetration of public
267 transit, and 17 percent for food from diet shifts.

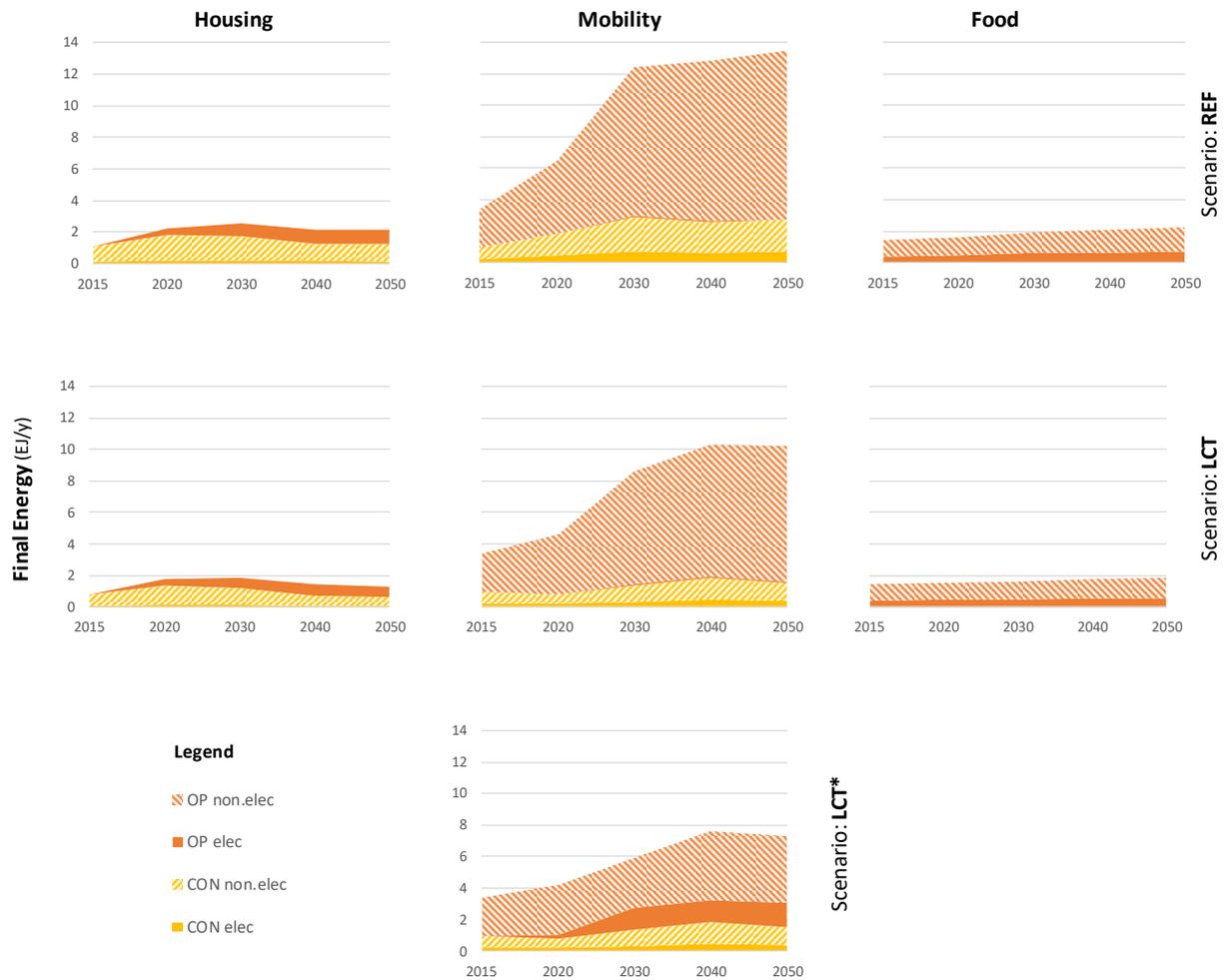
268 ***3.2. Final energy demand of services***

269 Combining energy intensities with service levels associated with basic needs, we can compare
270 the relative contribution of these services to aggregate energy demand. We see from Figure 3
271 that, by far, the operational energy for road vehicles (which is primarily diesel) dominates energy
272 demand for basic needs. This demand is about a factor of 2.5 greater than the next largest
273 category, the non-electric fuel demand in the supply chain to construct the vehicles. In the
274 building sector, the immediate demand is for bridging the existing housing deficit, but with time
275 the share of new homes to meet population growth in urban areas and building turnover remains
276 relatively constant. With this kind of decomposition, we are able to estimate the change in
277 energy demand for rural and urban homes from social policies that affect population growth,
278 such as those associated with women's education and associated changes in fertility, in addition
279 to energy policies. Introducing more energy-efficient buildings (LCT scenario) has an immediate
280 effect on reducing the construction energy for filling the housing gap. However, the reduction in
281 operative energy at stock level is slower due to relatively long building turnover cycles for
282 replacing the current stock.

283 We also see that a shift in mode shares towards public transit in cities (LCT scenario) without
284 any other changes can reduce mobility-related energy demand by over 25 percent. This shift also
285 reduces the construction energy for the fewer needed vehicles. Full electrification of public
286 transport (LCT* scenario) further reduces final energy by an additional 20 percent – an all-
287 electric bus fleet demands a third of the final energy demand of a conventional fleet. In contrast,

288 shifting construction practices to adopt more efficient building materials produces a higher
289 percentage reduction in building construction energy, but the aggregate impact is insignificant
290 compared to the shift in transport modes, also due to the slower uptake of new buildings. This
291 kind of comparison of impacts across services and at different points in the energy supply chain
292 is made possible by this service-driven model for indirect energy demand.

293 In comparison to buildings and mobility, energy use for food is relatively invariant across the
294 two scenarios. This is because food emissions in India are dominated by methane from rice,
295 while energy use is dominated by fertilizers⁶³, which vary comparatively less across grains. As a
296 result, emissions-reducing diets reduce rice use and methane, but only marginally reduce
297 fertilizer and energy use.



298

299 **Figure 3.** Final energy pathways for DLS scenarios for housing, mobility, and food in India.
 300 Demand side scenarios: reference (REF), low-carbon technologies (LCT), and low-carbon
 301 technology with full public transport electrification (LCT*). Breakdown by construction (CON)
 302 and operation (OP) energy and by electricity (elec) and other fuels (non.elec).

303

304 **3.3. Identifying mitigation priorities**

305 We apply carbon intensities of fuels to meet the above energy demand projections from two
 306 decarbonization futures at two extremes of ambition, one with current climate policy frozen (PS1),
 307 and the other achieving the 1.5°C target (PS2). In doing so, we illustrate the comparative mitigation

308 potential from different mitigation measures from the supply and demand side, and include
309 changes in how basic needs are met without reducing wellbeing.

310 First, note that the absolute emissions levels of the three demand categories are comparable (Figure
311 4), even though their final energy demand differs widely (Figure 3), with mobility dominating the
312 other services by over a factor of five. In the case of food, this is largely because of the dominance
313 of non-energy emissions from rice cultivation in food-related emissions. For buildings, this is in
314 part because of non-energy emissions from cement production and the relatively high share of
315 electricity in final energy, which has a high carbon intensity due to coal.

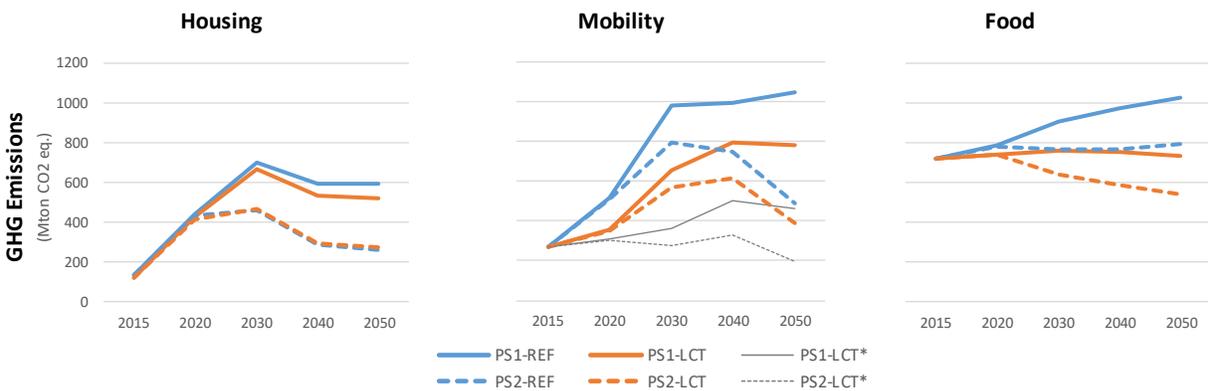
316 The relative impact of decarbonization and energy demand reduction differs for each service. As
317 discussed earlier, demand-side measures have a greater potential to reduce energy demand with
318 mobility compared to housing, which propagate to their respective emissions reductions potential
319 (straight orange lines in Figure 4). For the case of food, although energy demand doesn't reduce
320 from demand-side diet shifts, significant emissions can be reduced due to the avoidance of methane
321 emissions from shifts away from rice. This reduction exceeds the potential for emissions
322 reductions from the energy demand reduction in the other two services.

323 Assuming, hypothetically, that India decarbonizes the energy sector in accordance with a 1.5°C,
324 in absence of demand changes (dotted blue lines in Figure 4), the potential emissions reductions
325 by 2050 are on the order of 55 and 80 percent for housing and mobility respectively, but far less
326 for food, as expected, due to high non-energy emissions. Notably, for food, diet changes produce
327 comparable emissions reductions as does this ambitious shift to decarbonized fuel.

328 In housing, because of the dominance of electricity in energy demand, emissions reduction from
329 decarbonizing electricity production dominates overall mitigation potential, which is comparable

330 in both 1.5°C scenarios, with and without demand reduction. What emissions remain in both cases
 331 come from cement used in construction. In contrast, with mobility demand reduction through mode
 332 shifting has a substantial mitigation potential and enables quicker near-term emission reductions
 333 than for housing. With full electrification of public transport (LCT*), just from the combination
 334 of higher occupancy and efficiency with electric public transit, emissions can be almost halved by
 335 2050 without any decarbonization, while providing the same level of mobility to all.

336



337

338

339 **Figure 4.** Emissions pathways for DLS scenarios for housing, mobility, and food in India.
 340 Demand side scenarios: reference (REF), low-carbon technologies (LCT), and low-carbon
 341 technology with public transport (bus) electrification (LCT*) by 2030. Supply-side scenarios:
 342 current energy system (PS1) and 1.5°C (PS2).

343

344 **3.4. Recast of industrial energy demand**

345 The linkage of consumption to indirect *final* energy demand enables a broader picture of the
 346 economy-wide energy and emissions reduction potential from changes in consumption, and
 347 thereby a means to relate resource use directly to socioeconomic trends and material well-being.
 348 This in turn enables a more comprehensive analysis of sustainable development pathways

349 considering wellbeing and environmental impacts. Integrating IE methods and energy scenarios
350 allows recasting the industrial energy by the underlying driving services – rather than by sectors
351 – and further assess the impact of consumption changes and demand-side measures on energy and
352 environment. Our results for India show that providing basic services would require a considerable
353 amount of final embodied energy in 2015: 1.0 EJ for housing, 0.9 EJ for mobility, and 1.4 EJ for
354 food. One can compare these results with the current energy consumption for India⁶⁴ and estimate
355 the share of total industrial final energy that would be needed to satisfy basic needs, i.e. 11% for
356 housing, 10% for mobility and 14% for food in 2015. Such analyses can be extended to other types
357 of consumption, to characterize their economy-wide energy use. The linkage between service
358 demand and IAMs could also enable—through IE methods’ other environmental impact
359 indicators—broader sustainability assessments that examine alongside climate mitigation goals
360 other objectives among the Sustainable Development Goals (SDG), such as sustainable
361 consumption and production, or even health and wellbeing-related goals, since consumption can
362 be linked to basic human needs. Furthermore, representing energy embodied in products and
363 services in final – rather than primary – terms, makes it possible to decouple material energy
364 requirements and future changes in the energy supply sector. With this flexibility, it is possible to
365 explicitly assess consumption-side, energy demand and supply-side measures in climate
366 stabilization pathways.

367 ***3.5. Limitations and further research***

368 Some limitations apply regarding the data we used in LCA, representation of changes in the
369 manufacturing structure, and accounting of different types of fuel.

370 For the LCA methods, we relied on data from internationally recognized databases to estimate the
371 ratio primary-to-final energy and the share of electricity. This might not completely reflect the
372 supply chains in the analyzed country, India, due to potentially different production processes.
373 However, country-specific life-cycle inventory data are mostly not available for developing
374 countries. Process-based LCA involves truncation errors as it depends on pre-defined system
375 boundaries⁶⁵. The magnitude of such errors depends on the cut-off criteria and sector groups. Thus,
376 the comparability of LCA and EEIO results might be limited due to such issues as different system
377 boundaries and different treatment of capital inputs. To further ensure the direct comparability of
378 the results across demand categories, future research could examine the use of hybrid IO-LCA and
379 also compare with the results given in this work.

380 In our scenarios, we represent key technological and demand changes for housing, mobility and
381 food driven by targeted policies. Regarding future changes in manufacturing processes, our
382 analysis is limited to material efficiency improvements for building construction. A broader
383 representation of future changes in the manufacturing structure along different scenarios is
384 currently missing. With improved data availability and accounting of such changes in LCA-IO
385 methods^{66,67}, structural and technological changes could be explicitly represented in the model.

386 In our methods we focused exclusively on the energy losses in the electric sector losses to
387 approximate the difference between primary and final energy. Future studies should further
388 characterize the efficiency losses in other fuel supply chains. Recasting of service-driven
389 demands for key industries, such as cement, steel, aluminum, pulp and paper, and petrochemical
390 is also suggested. This study presented a first step towards linking Industrial Ecology tools and
391 IAMs through a simplified methodology for decarbonization pathways. Future work should
392 focus on further integration with IAMs to improve the comparability of results across end-use

393 services and upscaling for more comprehensive and economy-wide accounting of services, as
394 well as broader geographical coverage. This will enable the development of more robust and
395 comprehensive climate stabilization scenarios, including the evaluation of trade-offs between
396 material and technology use, energy demand and decarbonization options.

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403 Alessio Mastrucci, Jihoon Min, Narasimha D. Rao.

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408 **Associated Content**

409 **Supporting Information.** The following files are available free of charge.

410 Final energy accounts for Life Cycle Assessment and Input-Output, carbon emission intensities,
411 and description of the Decent Living Scenarios, including narratives, assumptions, detailed input
412 data, calculations and results. (PDF)

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