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Perspectives on Quantifying and Influencing Household Metabolism

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Abstract

Household metabolism is a concept that is concerned with the analysis of stocks and flows of energy, matter, and information at the household scale. This paper starts by providing a brief overview of the concept of household metabolism. Rather than attempting an in-depth review and analysis of this field, the article subsequently maps the contributions and perspectives of a broad variety of research traditions that have an interface with the concept of household metabolism. Next, this paper highlights a number of controversial issues connected to household metabolism, and studies at the interface of household metabolism. Finally, this paper argues that the concept of household metabolism can provide valuable help in diagnosing misalignments between enacted system dynamics and expressed societal goals, and can help to design research that facilitates their alignment.

Keywords: household metabolism, material flow analysis, waste discharge, resource use

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1. Introduction

Human societies are an integral part of the ecosphere and interact with other entities of the ecosphere through stocks and flows of material, energy, and information. The resemblance of this exchange to the transformation of stocks and flows by organs in animate beings led to the concepts of "metabolism of cities" (Wolman 1965), "industrial metabolism" (Ayres 1989), "metabolism of the anthroposphere" (Baccini and Brunner 1991), "social metabolism" (Fischer-Kowalski and Haberl 1993), and "household metabolism" (Noorman and Schoot Uiterkamp 1998). These concepts prepared the ground for the analysis of stocks and flows of material, energy and information for different system boundaries and at different spatial levels. Common scopes of such analyses are specific countries (e.g. Bin and Dowlatabadi, 2005), groups of countries (e.g. Ott and Rechberger 2012), regions (e.g. Faist et al. 2001), cities (e.g. Kalmykova et al., 2012), neighborhoods (e.g. Codoban and Kennedy 2008), industrial sectors (e.g. Antikainen et al. 2005), the sum of private households in a given country or region (e.g. Moll et al. 2005), or individual private households (e.g. Kotakorpi et al. 2008).

A recent special issue of the *Journal of Industrial Ecology* on Frontiers in Socioeconomic Metabolism Research was dedicated to a review of research progress and policy impacts of socio-economic metabolism research (Schandl et al. 2015). Whilst until the 1990s studies on the environmental impacts of economic activity focused on production processes, the focus of socio-economic metabolism research has since then been broadened to also include consumption and final demand as drivers of societal metabolism (Di Donato et al. 2015). Given that much of the environmental impacts caused by resource exploitation and waste management are ultimately driven by household consumption, household consumption has been highlighted as a key area requiring attention (Di Donato et al. 2015, Doyle and Davies 2013, Hertwich 2011, Lenzen and Peters 2009, Moll et al 2005, Noorman and Schoot Uiterkamp 1998, Tukker et al. 2010).

Strictly speaking, the quantification of household metabolism is concerned with physical flows (both direct resource flows through households and flows indirectly required to satisfy household consumption) and related environmental impacts. When framed as a research field within socio-economic metabolism research, household metabolism studies are often characterized by a macro-level approach, that is, household metabolism is understood as resource consumption and emissions ultimately driven by aggregate household consumption. Here, the focus often is on energy consumption and greenhouse gas emissions (Di Donato et al. 2015, Schandl et al. 2015), a focus already found in pioneering household metabolism studies in the 1970s that were motivated by investigating energy conservation opportunities (e.g. Bullard and Herendeen 1975) as well as in later studies (e.g. Lenzen 1998).

However, the rate of household metabolism depends on a wide variety of factors (Moll et al. 2005, Noorman and Schoot Uiterkamp 1998) such as household income, local availability of resources, policy, legislation, practices, and values. Therefore, also individual households can be an important unit of analysis for studying and promoting pro-environmental behavior (Reid et al. 2010; Baker et al. 2007). On a yet higher level of disaggregation, the demand for resources and the related environmental impacts are driven by different household activities and practices. So demands and impacts can also be analyzed in relation to different users, household activities, or practices. As a result, a broad variety of studies can be related to household metabolism in that they seek to describe factors that influence the rate of household metabolism, or to reduce the rate of household metabolism through the promotion of more sustainable consumption patterns. Such studies, which are often rooted in the social sciences, go beyond a purely physical notion of household metabolism and focus amongst others on behavioral aspects of consumption and consumption choices (e.g. Tobler et al. 2011a), household practices (e.g. Gram-Hanssen 2010), or co-management of household practices (e.g. Strengers 2011a).

The overall scope of this paper is twofold: to place the concept of household metabolism in a wider context by highlighting interfaces between the concept of household metabolism and other research fields that deal with factors influencing the rate of household metabolism, and also to highlight the usefulness of household metabolism in diagnosing misalignments between enacted system dynamics and expressed societal goals, which both influence the rate of household metabolism. First, this paper describes the concept of household metabolism. Second, the contributions of various research fields to understanding and influencing household metabolism are reviewed. Third, a number of critical voices are presented which point out potential weaknesses and blind spots of studies aiming to describe or reduce the rate of household metabolism. Fourth, a number of further research opportunities are sketched and the value of the concept of household metabolism in achieving alignment between different driving forces influencing the rate of household metabolism is emphasized.

2. Conceptual Model of Household Metabolism

The term household metabolism is usually used to refer to flows of matter and energy resulting from household consumption. The concept encompasses both direct flows (i.e. physical flows of matter and energy through households) and indirect flows (i.e. physical flows required to realize the direct flows through households) (Noorman and Schoot Uiterkamp 1998). Households are defined as socio-economic entities consisting of one or more individuals who live together occupying all or part of a dwelling, and are embedded in the socio-economic system as illustrated in Figure 1.

In a first approximation, the analysis of household metabolism could be limited to the physical household (walls and fence of yard as boundary). This would enable a comprehensive registration of material stocks, but many physical flows could not be observed, particularly those connected with the production and disposal of goods (e.g. flows in the agricultural sector) and the provision of services (e.g. flows connected with tourism). In order to account for the flows that are not physically contained in a product or service (i.e. indirect or virtual flows), however, products and services need to be followed upstream and downstream outside the strict boundaries of the physical household (e.g. Lenzen and Peters 2009).

At least in theory, every material and energy requirement connected to a product or service demanded by a household could be measured in situ at the location of production or disposal. Such upstream and downstream measurements would require sensing of material flows in hundreds of enterprises and governmental bodies, which would be a daunting task associated with high costs. Even if this were the correct approach to be able to assess the effect of individual consumption choices, and factors influencing individual consumption choices, it is hardly feasible to apply such detailed process analysis in practice. Still, it is possible to estimate the total material requirements and emissions of a product or service by combining detailed data about the particular product or service with average data for upstream and downstream processes in the supply chain, which is a common approach in life cycle assessment studies. This approach is also referred to as bottom-up approach to the quantification of household metabolism (Di Donato et al. 2015). The principal alternative is environmentally extended input-output analysis based on national economic statistics, which basically reallocates resource consumption and emissions from different industrial sectors to household consumption. This approach is also referred to as top-down approach to the quantification of household metabolism (Di Donato et al. 2015). It is also possible to combine bottom-up and top-down approaches in a hybridized methodology (Alvarez-Gaitan et al. 2013, Di Donato et al. 2015). Recently, the usefulness of data mining ("big data") and advanced information and communication technology (ICT) tools as sources of personal and geo-referenced data on consumption activity was highlighted (Hubacek et al. 2014).

Previous studies considered for instance total energy use (Carlsson-Kanyama 2002), total natural resource consumption (Kotakorpi et al. 2006), and lifecycle impacts of housing and mobility demand (Saner et al. 2013). Although the analysis of household consumption in terms of physical flows reveals variations in stocks and flows between households, the use of average values for flows located upstream and downstream of households means in practice that impacts associated with production and waste management are not fully responsive to the consumption choices of a particular household, at least in the model world.

3. Interfaces Between Household Metabolism and Various Research Traditions

A broad variety of research fields relate to the concept of household metabolism in one way or another. Here we focus on several research disciplines: firstly those discussing the multiple roles of households as well as decision-making and resource allocation within households; secondly those concerned with quantifying the type and magnitude of the flows entering and leaving the household, and with relating these flows to environmental impacts; and thirdly those focusing on understanding what motivates the type and magnitude of the flows, and interested in how the type and magnitude of flows can be influenced.

3.1. The Household as Crucible for Pro-Environmental Behavior

Reid and colleagues (2010) highlighted the importance of the household as a unit of analysis for studying and promoting pro-environmental behavior, and argue for understanding the household as a unit within the meso level of reality through which macro level change can be observed and micro level activity can be contextualized (i.e. individuals are embodied into their broader environment through the household as an organizational unit of the society). Whether the household or the individual should be focused on can be debated, however, and depends on decision-making in households. Understanding decision-making in households and the role of individuals in a household's demand system requires a distinction between different types of household consumption.

3.1.1. Types of Household Consumption

When analyzing household consumption it is common practice to distinguish private goods and household goods (Bergstrom 1995; Bruyneel et al. 2012; Chen and Wooley 2001; Ebert 2013; Haller 2000). Private goods can only be consumed by one household member, while household goods are jointly consumed, either directly or as positive externality, thereby providing utility for more than one household member (e.g. housing expenditures, car usage, touristic trips). Household members are not rational in the sense of classic economic theory. Emotional ties between household members lead to so-called 'caring preferences' or 'household preferences', which means that the welfare of one household member derives utility for another household member because he or she cares about her or him. For example in the household of a couple, a male shower gel is consumed only by one member of the household, hence it is a private good; but on the other hand it is easy to see that this good will derive utility for the other member of the household as well because she cares for her partner's hygiene, comfort, and odor. Purely private goods thus are rare. This suggests there is value in the analysis of household consumption patterns rather than individual consumption patterns, because most purchases are plausibly a result of some joint decision-making process.

3.1.2. Decision-Making in Households

Decisions with regard to intra-household resource allocation involve mainly problems of labor supply, choices of saving opportunities, and consumption. Within socio-economic metabolism research, consumption choices are the most significant decision object. The consumption choices of households are influenced at an individual/family level, for instance by household size and structure, income, dwelling type, psychological factors (e.g. motives, needs, perception, education, attitudes, personality), lifestyle (e.g. mode of transport), information and knowledge. In addition, households are affected by external influence factors (e.g. policy, technology, culture, demographics, social status, reference groups) (Bovée and Thill 1992). The influence of family structure, demographic changes as well as cultural values are intensively examined elements of the marketing environment (Kotler and Armstrong 2013; Keegan and Green 2013), which continuously undergoes transformation. The change in economic conditions was especially significant in the last decades (Keegan and Green 2013).

Frequently purchased, cheaper goods with lower unit cost (e.g. food) are often subject to habitual (automatic) consumption, whereas rarely purchased or more expensive goods are normally subject to decision-making (Kirchler 1995). The two main conceptualizations of decision-making in households are the unitary household model and the collective model. Early consumer theories considered families (households) as single decision-making units maximizing a 'family utility function', without taking intra-household factors into consideration. Other authors are in favor of a collective model of household consumption due to its higher descriptive value (Bateman and Munro 2009; Bourguignon et al. 1993; Bruyneel et al. 2012; Browning et al. 2006; Couprie et al. 2010; Dauphin and Fortin 2001; Haller 2000; Munro 2009; Vermeulen 2002).

In the collective model, a household is seen as "microsociety" with individual preferences (Vermeulen 2002) and pluralistic decision-making (Bergstrom 1995). Collective models assume that household decision-making (like group decision-making) may result in better choices due to more information and more correct information processing (Munro 2009). The household utility function is affected by factors such as caring preferences, budget constraints, wealth contributed by each household member, distribution of income within the household, or age and education of each household member (Browning et al. 2006). Household demand is the result of the individual household members' utility functions (Bruyneel et al. 2012) and bargaining power. The bargaining power of household members is determined by factors such as the legal framework, institutional practices, cultural norms, wage, non-labor income, prices of (private) goods and services, and taxes (Chen and Wooley 2001; Vermeulen 2002). It is important to note that children and adolescents may have a significant influence on economic decisions in households (e.g. education), and may become equal to the parents above the age of sixteen (Dauphin and Fortin 2001). Furthermore, Fujii and Ishikawa (2013) suggest that goods consumed by children are household goods because parents care about their children's welfare. Caring preferences towards children can also affect other household members' private consumption (e.g. abstinence from tobacco consumption) or household consumption (e.g. higher degree of heating).

3.1.3. Household Decision-Making in a Broader Context

Household consumption, however, is not merely the result of purchasing needed commodities and services. Decisions about household consumption, or lifestyle choices in general, are also influenced by a number of driving forces beyond the household and the individuals constituting the household. These driving forces can be found in different contexts: global context (e.g. globalization, individualization, new technologies) (EEA 2005), structural context (Sanne 2002; Jackson and Papathanasopoulou 2008; Vergragt et al. 2014) such as urban structure, consumer culture, work, supply chains (especially food and energy), as well as individual context (e.g. needs, group identification, income).

3.2. Advances in Quantifying Household Metabolism

Physical flows can be quantified at different levels of disaggregation, for example at the level of an individual household, at the level of individual fixtures/appliances or fixture/appliance groups, or even at the level of individual activities or practices. Flows can be quantified in terms of different products or layers, and enter and leave households through various pathways which may be considered in two major groups: those that travel through public mains, and those that do not but travel via for example retail trade or waste collection schemes (see Figure 2).

3.2.1. Goods Supplied through Public Mains

The supply of goods through public mains is normally quantified using meters or sensors. For quantification of flows at the level of an individual household, at least one meter per flow is required. Utility companies often provide such meters for billing purposes. Although modern smart-meters commonly have sampling intervals of 15 minutes, water and energy bills usually state monthly consumption values only. In case disaggregated consumption data per fixture/appliance is required, two approaches are possible. The first approach is straightforward, at least in theory, and consists of placing one meter on every fixture/appliance of interest. In practice, however, this approach requires a substantial number of meters and may be hampered by costs and cumbersome installation. The second approach builds on interpretation of the signal from a single meter using pattern recognition techniques and algorithms. Pattern recognition allows for a considerable reduction of the number of sensors to be deployed, often to as little as one single sensor per flow to be quantified; the downside is that not all events may be correctly classified and assigned to a given fixture/appliance.

Human-computer interaction (HCI) and ambient intelligence research have contributed substantially to enabling data collection at this high level of disaggregation through the development of advanced sensing technology and disaggregation algorithms. The key motivations behind these developments include developing and testing eco-feedback technology (Sundramoorthy et al. 2011; Froehlich et al. 2011a), improvement of health-care systems through activity sensing (Martín et al. 2013; Chiriac et al. 2011; Kushiro et al. 2009), and smart homes (Ding et al. 2011; Rodgers et al. 2010).

For water usage, the sensing and disaggregation approaches tested by the research community include sound-based distributed sensing (Fogarty et al. 2006; Ibarz et al. 2008), vibration-based distributed sensing (Kim et al. 2008), pressure-based single-point sensing (Froehlich et al. 2011b; Larson et al. 2012), and disaggregation based on low sample rate smart meters (Chen et al. 2011) or high sample rate smart meters (Kim et al. 2009). A comprehensive overview of sensing water consumption is presented in Froehlich (2011). Sensing and disaggregation approaches for electricity usage include distributed sensing on the breaker board level (Lin et al. 2010), single-point sensing and disaggregation based on high frequency electromagnetic interference patterns (Gupta et al. 2010), and disaggregation based on high sample rate flow meters and additional side information (Kim et al. 2009). A comprehensive overview is presented in Froehlich et al. (2011a) and Zeifman and Roth (2011). For gas usage, Cohn et al. (2010) tested a sound-based single-point sensing and disaggregation approach.

3.2.2. Services and Goods not Supplied or Discharged through Public Mains

Supply channels other than public mains supply include retail trade or direct acquisition (e.g. home-grown food). The range of goods acquired through these latter channels is much more varied than for goods supplied in public mains and mainly includes durable goods (e.g. household appliances, furniture) and consumer goods (e.g. detergents, food). The composition of these goods is much less homogeneous than for goods supplied in public mains. Packaging material, used products, and biodegradable waste are disposed of by households through several formal or informal pathways. Waste flows can be grouped into recyclables, biodegradable waste, bulky waste, hazardous waste, and residual waste. Recyclables, for instance, could be further disaggregated into used products and packaging material, which in turn could be divided into paper packaging, metal packaging, plastic packaging and so forth.

Quantifying the consumption of services, goods not supplied through public mains, and waste generation is complicated due to batch-wise supply and discharge through several pathways as well as the heterogeneous composition of the related physical flows. If these flows are accompanied by a monetary flow, their magnitude is normally registered electronically. This is the case for example for fuel purchased at petrol stations, consumer goods purchased through retailers, and waste discharged through waste collection systems with weight-based billing. This information is usually available to customers, though not always in a convenient format for subsequent data storage and analysis. Some information may be available through retailers based on customer fidelity schemes, and changes in legislation on data disclosure (Thaler and Tucker 2013) could imply a significant boost for the availability of such data. Thaler and Tucker (2013) for instance report that Tesco, the largest supermarket chain in Britain, plans to allow members of its customer fidelity scheme to make use of their own data collected through the scheme.

Alternatively, data can also be collected manually, through household documentation in the form of a diary or journal. Kotakorpi and colleagues (2008) for example monitored housing, mobility and leisure time activities, tourism, food (nutrition), packaging and wastes, and household goods and appliances through questionnaires. In other studies, households were asked to sort waste in different fractions and record the weight of the respective waste fractions on a daily basis (Abu Qdais et al. 1997; Bandara et al. 2007), or to sort recyclables and biodegradable waste in different fractions on a daily basis for subsequent manual analysis and data collection on a per unit basis by a research team (Harder et al. 2014).

Household documentation can also be facilitated by smartphone mobile applications: for example, Siek and colleagues (2006) tested a nutritional monitoring application; Froehlich and colleagues (2009) developed a mobile tool for sensing and providing feedback about personal transportation habits and choices; Harder and colleagues (2014) conceived a mobile application for recording the purchase and consumption of food products as well as the generation of food waste; and examples are emerging of applications combining tagging and reading devices to minimize the impact of wardrobe management (Peters et al. 2014).

3.3. Perspectives on Understanding and Influencing Household Metabolism

When it comes to understanding resource consumption and waste generation at the level of households, several approaches can be applied. For example, a large number of individual households can be studied and statistical techniques can be applied to reveal the influence of certain independent variables (e.g. socio-economic status, size of the house, household income, family size, etc.) on certain dependent variables (e.g. electricity consumption, water consumption, waste generation, ecological footprint, etc.). For example, Hunter et al. (2006) applied a diary-based data acquisition methodology to estimate and compare the ecological footprint of different individual households for goods purchases, transport, and waste generation. Similarly, resource consumption and waste generation could also be modeled as function of household characteristics (Baker et al. 2007; Saner et al. 2013; Stamminger 2011). A different approach is to connect resource consumption and waste generation to user behavior and consumption habits. The remainder of this section presents several distinct types of studies that all have in common that they seek to understand factors influencing household metabolism and/or to influence user behavior and consumption patterns. However, the different types of studies are distinct in the underlying assumptions, the research approach chosen, and the research methods applied.

3.3.1. Focus on the Household: Roles and Motivations of Households

Among the key functions of households in the economic system are the supply of labor and the provision of financial capital through household savings. Furthermore, households are important objects of fiscal politics (e.g. balance of taxes and transfers, income allocation). The most important activity of households in the context of socio-economic metabolism research, however, is consumption. Bovée and Thill (1992) describe consumption as an exchange process between customer and marketer, where elements of value (i.e. goods, services, ideas) are exchanged in return for a monetary value, time, votes, or a desired behavior. An overview of the role of households in the economic system is provided in Samuelson and Nordhaus (1996).

According to basic (classical and neoclassical) economic theory, households aim to maximize the utility at the household level, whilst corporations aim to maximize profit at the corporate level and governments aim to maximize social welfare at the regulatory level. However, such simplification of human motivations omits important motivational factors such as social interest, cooperation, altruism, and welfare of employees (Beaudreau 2012; Ghosh et al. 2011; Lux 2003). Although the complexity of motivational factors was well known in classical economic theory (Lynne 2006), the complexity (and realism) of economic notions and models were decreased during formalization of economic theory (Beaudreau 2012). More advanced economic models include various aspects of human behavior such as social interactions, reference dependence, evolving preferences, habit formation, social preferences, or adaptation and learning (Ho et al. 2006; Safarzynska 2013). Beaudreau (2012) for instance established a "humanistic model of economic behavior" integrating different motives (based on Maslow's hierarchy of needs) as well as genetic, hormonal and cultural vectors.

3.3.2. Focus on the Household: Lifestyle Segmentation and Social Inequality

Various means of segmenting households have been considered as a way of trying to understand the intrinsic motivations and constraints towards different types of consumption. Much of this work is driven by academic interest in marketing and behavioural science. Greenberg and Frank (1983) for example studied the influence of personal interests on the consumption of different types of television programming, segmenting adult males into those whose lifestyles could be characterised by "mechanics and outdoor life", "money and nature's products" or "family and community centred". A more recent work of this type used values, life visions and aesthetic styles and performed statistical cluster analysis (Vyncke 2002). The results suggested that such "psychographic" segmentation has more predictive power than traditional demographics (gender, age, social class, life stage) with respect to forecasting individuals' preferences for consuming cars, tourism and media products. On the other hand, Vyncke noted that the capacity of such analysis to explain actual consumer behaviour was poorly documented. This general perspective is supported by Zepeda and Nie (2012) who segmented Americans into "food related lifestyle" segments: adventurous, careless, conservative, rational and uninvolved. From a range of parameters correlated with these segments, they found that environmental concerns were more important than family composition or income in terms of predicting the purchase of organic or local produce, but practical constraints such as the presence of a farmers' market, were just as important as environmental concerns. This caveat was the more pronounced in a study by Newton and Meyer (2014) which focused on attitudes, opinions and intentions specifically related to environmental matters, defining three lifestyle segments: "committed greens", "material greens" and "enviro-sceptics" living in Melbourne, Australia. There was a strong relationship between membership of a segment and various socio-demographic attributes, but little correlation with actual environmental behaviours such as energy and water consumption. Factors such as income, living in the suburbs and having a family appeared to play a role in constraining both membership of the "committed greens" group, who had enough income to contemplate tax increases and higher utilities costs to support environmental causes, while on the other hand those on lower incomes appeared constrained to causing less environmental damage in damage categories such as those correlated with housing space. Chancel (2014) looked at generational effects on lifestyle segmentation and social inequity, and correlated the effect of date-of-birth on greenhouse emissions for American and French citizens. He found that middle-aged French people had much higher emissions than their predecessors and successors, while the influence of age was unimportant in the United States. On the other hand, in both countries, income inequality played a major determining role, with the greenhouse emissions of the top decile of Americans four times higher than the bottom decile, and the bottom decile similar to the top decile of French people. The effect of income inequality within generations was smaller in France (less than factor 3 between the top and bottom deciles).

3.3.3. Focus on the User: Understanding Individual Users

Several studies sought to understand factors influencing individual user behavior. Based on in-depth interviews with 50 householders, Crosbie and Baker (2009) for example investigated why people react to particular energy-efficiency interventions in the ways that they do. Holden and Linnerud (2010) analyzed the relationship between environmental attitudes and energy use in the home and for transport by Norwegian households. Isenhour (2010) investigated difficulties and barriers Swedish consumers faced in their attempts to reduce their environmental and social impacts. De Vries and colleagues (2011) studied how the enactment of intentions is thwarted by acting and non-acting habits. Food preferences and the willingness to adopt pro-environmental food preferences were studied by Tobler and colleagues (2011a), who compared beliefs about ecological food consumption and consumers' willingness to adopt such behaviors, and investigated how different motives and food-related attitudes influenced consumers' willingness to reduce meat consumption and to buy seasonal fruits and vegetables. Gwozdz and colleagues (2013) performed a similar analysis relating attitudes to willingness to purchase more sustainable clothing. Tobler and colleagues (2011b) also studied how consumers assess the environmental friendliness of vegetables. Thomas and Sharp (2013) investigated how social norms, habits and identities influence recycling behavior. An illustrative review and research agenda on encouraging pro-environmental behavior is provided by Steg and Vlek (2009), who distinguish three types of factors influencing pro-environmental behavior: motivational factors, contextual factors, and habitual behavior. A thorough discussion on influencing behavior through contextual influences is provided elsewhere (e.g. Dolan et al. 2012; Moseley and Stoker 2013).

3.3.4. Focus on the User: Persuasive Technology and the Role of Feedback

Persuasive technology refers to interactive technologies and services that are designed to influence people's attitudes and stimulate behavior change (McCalley et al. 2011; Roubroeks et al. 2011). Persuasive technology can be seen as a particular case of design with intent, that is, one way of using product and system design to influence user behavior (Lockton 2012). One example of persuasive technology is eco-feedback technology, that is, technology aiming at reducing environmental impacts through providing feedback on individual or group behaviors. Primarily, eco-feedback is meant to facilitate informed decision-making. Feedback of water and energy consumption to individual households has been thoroughly investigated elsewhere (Froehlich 2011; Sundramoorthy et al. 2011). Other studies were limited on energy consumption and investigated the impact of eco-feedback information representation on energy consumption behavior (Jain et al. 2013), compared factual feedback (i.e. numerical consumption feedback) and ambient feedback (i.e. changing light color) (Maan et al. 2011), or assessed whether eco-feedback gives rise to any significant increase or decrease in household energy consumption (Pereira et al. 2013). Fischer (2008) reports that eco-feedback on energy consumption (electricity in particular) usually seems to work, leading to savings between 5 and 12%, but acknowledges that some studies report no findings at all. This points at the importance of the design of eco-feedback and other persuasive technologies. In order to facilitate analysis and design of persuasive technologies, Fogg (2009) proposed a behavioral model based on three factors: in order to perform a target behavior, a person must have sufficient motivation, sufficient ability, and an effective trigger. Thørgersen (1994) proposed a similar triumvirate of motivation, ability and opportunity, the opportunity being defined by external infrastructural and economic factors. By comparing the feedback loops underlying persuasive technologies and reflective learning, Müller and colleagues (2012) sketched a design space between reflective learning and persuasive technologies. Ford and Karlin (2013) presented a cognitive approach to the design of graphical display in eco-feedback, concluding that eco-feedback displays appear to be more successful when they contain fewer data points and/or include pictures. Finally, Hekler and colleagues (2013) discussed how HCI researchers could contribute to the development and refinement of behavioral theories.

3.3.5. Focus on Practices: Co-Management of Resources

Sometimes the persuasion needs to occur during the design process so as to create systems that constrain the user to subsequently behave in the desired way. One example of this is the development of tools to popularize the visualization of the environmental benefits of alternative designs. Schulz and colleagues (2012) produced such a tool to enable private citizens to engage with utilities in discussing water saving designs at the household and community scale. Empowering the consumer gives the subsequent constraints more legitimacy. A more comprehensive approach is to integrate such systems with processes of regulatory approval. BASIX is an example of an online tool where citizens are allowed to experiment with alternative designs for a home construction or renovation. Once they develop a design that meets the state government's water and energy saving targets, the data output of the tool is used as a prerequisite for a successful development application (www.basix.nsw.gov.au). Other studies investigated how utility companies can jointly manage of energy and water practices with households (Strengers 2011a).

3.3.6. Focus on Practices: Practice Theory and Practice-Oriented Design

The basic assumption behind practice theory is that consumption occurs as items are appropriated in the course of engaging in particular practices, and that being a competent practitioner requires appropriation of the requisite services, possession of appropriate tools, and devotion of a suitable level of attention to the conduct of the practice (Warde 2005). Among the practices analyzed in the literature are residential heat comfort practices (Gram-Hanssen 2010a; Doyle and Davies 2013; Kuijer and de Jong 2012), standby energy consumption (Gram-Hanssen 2010b), bathing practices (Scott et al., 2012), and cooking practices (de Jong et al. 2013).

3.3.7. Focus on Innovation: Living Labs

A recent trend in user-centered research are living laboratories, which are usually referred to as living labs. The term living lab is used to refer to both an innovation methodology and the arena or facilities created for its practice (Almirall et al. 2012; Ståhlbröst 2012). From the methodological perspective, living labs are networks composed of heterogeneous actors, resources, and activities that integrate user-centered research and open innovation (Leminen et al. 2012). From the infrastructure perspective, living labs are facilities that enable experimentation and co-creation with users in real-life environments (Sundramoorthy et al. 2011; Keyson et al. 2013). Living labs can be relevant platforms to create innovation for sustainability (Liedtke et al. 2012) and as such can be useful to study how user behavior or certain household practices can be influenced or altered (Scott et al. 2012), or to develop and test persuasive technology (Sundramoorthy et al. 2011).

3.3.8. Focus on the Context: Household Metabolism in a Multi-scale Perspective

When it comes to the analysis of household metabolism, an interesting opportunity emerges when the analysis of household metabolism is embedded in the analysis of socio-economic metabolism across multiple scales (Giampietro et al. 2009; Sorman and Giampietro 2011). In such a framework, the key roles of households (i.e. labor supply and final consumption) are considered and the interrelations between households the socio-economic system (e.g., demographics, technological regimes) and the environment (e.g. resource availability) are explicitly taken into account. Embedding household metabolism research in a multi-scale perspective would combine the merits of household metabolism research in terms of the high level of detail provided with a rigorous consistency check between scales. In other words, a multi-scale approach would reveal if changes envisioned for the household level are in line with, or contradictory to dynamics and boundary conditions on higher scales. The multi-scale perspective has recently been applied to for instance energy systems (Ramos-Martín et al. 2009), biodiesel production (Borzoni 2011), urban waste (D'Alisa et al. 2012), water use (Madrid et al. 2013), and land use (Serrano-Tovar and Giampietro 2014). Recent developments in multiregional input-output models such as EORA (Lenzen et al., 2013) will facilitate this perspective.

3.3.9. Focus on the Effectiveness of Interventions: The Role of the Rebound Effect

A crucial issue to be analyzed in the context of household metabolism research is the rebound effect. It is generally referred to as an increment in consumption and associated environmental impacts that offsets the effects of a measure taken to reduce environmental impacts (Hertwich 2005). Early examples exist: when energy efficiency measures were introduced to energy policy in the aftermath of the oil crises in the 1970s, it became apparent that increased energy efficiency does not necessarily lead to reductions in energy demand (Hertwich 2005). More recently, several studies have focused on estimating the magnitude of the rebound effect associated with energy services such as lighting, space heating, and mobility (Sorrell et al. 2009). Examples of the rebound effects that have been described in the scientific literature include: when the savings from a reduction in car-ownership are spent on air travel, and the reduction in greenhouse gas emissions associated with less private driving are offset by an increase in emissions from air travel (Ottelin et al. 2014); when the increase in energy efficiency of heat pumps leads to longer heating periods and heating of larger volumes of space (Winther and Wilhite 2015); when the adoption of renewable energy technology (e.g. solar hot water and photovoltaic systems) leads to an increased energy demand (Havas et al. 2015); when the reductions in environmental impacts related with commuting obtained through increased telework activity are offset by an increase in home-related environmental impacts (Kitou and Horvath 2003, Kitou and Horvath 2008); or when the development of information and communication technology stimulates additional demand for mobility that may exceed the effect of substituting commuting (Aguilera 2008, Mokhtarian 2003, Mokhtarian 2009, Ahmadi Achachlouei and Hilty, 2015).

Several studies also highlight that the rebound effect is heterogeneous. For example, Grabs (2015) investigated the rebound effects associated with a shift to a vegetarian diet. The analysis was performed for different income deciles in Sweden, and the study found that the GHG rebound effect was 87% in the lowest income decile, while only 25% in the highest one (Grabs et al. 2015). Based on the German Mobility Panel, a household-level travel survey, Frondel and colleagues (2012) investigated rebound effects in private transport and found that the rebound effect following efficiency improvements is significantly higher in households with low mileage than in households with high vehicle mileage.

Many studies aiming to quantify rebound effects have a focus on macro effects or a sectoral focus (e.g. Dahmus 2014). However, as pointed out by Binswanger (2001), the rebound effect arises because technological improvements evoke behavioral responses. Research at the meso- or microscale, with a detailed temporal analysis of consumed goods and services at the level of individual households or individual household members, would allow for deeper understanding of the rebound effect. Ahmadi Achachlouei (2015) suggests that systems dynamics and agent-based modelling approaches may also be useful here. While agent-based approaches provide more detail for spatially explicit complex systems, they require more effort to implement.

4. Critical Voices regarding Research at the Interface of Household Metabolism

This paper so far introduced the concept of household metabolism and mapped a number of interfaces between the concept of household metabolism and a variety of research fields. Most research relating to household metabolism aims at making important contributions to the sustainability transition through reducing rates of household metabolism. The growing body of research at the interface of household metabolism would lead one to assume that this type of research lives up to its aspirations, namely the reduction of the material flows and environmental impacts of (household) consumption. However, there are a number of controversial issues as well as critical voices that provide arguments to assume the opposite, namely that not all research at the interface of household metabolism does, or can, live up to its aspirations. These aspects will be discussed in the remainder of this section.

4.1. Limitations of Focusing on Individuals and Households

The logics of citizen consumers as end-users of products and services meets provider logics at the consumption junction (Spaargaren and van Vliet 2000). For example, developers are interested in establishing shopping spaces outside the town because of the lower cost of available land. This allows for keeping prices lower in the shops outside the town, which meets consumer needs to find various goods and services in one place and at competitive prices. But the increasing demand for out-of-town shopping also results in increased need for individual mobility. Individual actions and the higher-level structures are continuously reinforcing each other, which can lead to lock-in effects. Lock-in aspects can be analyzed through different of lenses (Vergragt et al. 2014): a financial and investment lens (e.g. existing infrastructures in transport, energy supply, and water supply), a cultural lens (e.g. consumerist culture), an institutional lens (e.g. legislation, socio-cultural norms, financial system), a socio-psychological lens (individual behavior and motivations), and governance lens (e.g. power relationships, political systems). Consequently, the objective of research at the interface of household metabolism should be twofold: to facilitate reduction of the rate of household metabolism at the household level, and to identify and facilitate modification of higher level structures that lock households in an unsustainable lifestyle, particularly with regard to purchasing, housing, mobility and energy supply.

Maniates (2001) suggested that a privatization of responsibility, which results from focusing on individual and household consumption, actually hampers the reduction of resource consumption and waste generation since the nature of the public debate is transformed: the focus is on personal behavior rather than on the structure and the dynamics of the socio-economic system that perpetuates and reinforces environmental degradation. Hamilton (2010) hence suggests that, at the level of households, a 'politics of downshifting' (i.e. asking people to reflect whether a consumerist lifestyle actually makes them happy) may prove far more effective in promoting environmental protection and reduced consumption than a focus on physical flows related to household consumption and the consequences related to resource exploitation. A practical example of this is the idea of "slow fashion" in which the production of more durable garments facilitates recycling (Peters et al. 2014). However, breaking down structural lock-in may also require macro-level remodeling of technological, social and political systems.

4.2. Limitations of Persuasion

Brynjarsdóttir and colleagues (2012) highlight that eco-feedback and other persuasive technology, rather than tackling the complex problem of sustainability as a whole, reduces sustainability to a limited set of individual consumer behaviors that have a fairly clear and direct impact on sustainability understood as a form of resource management. As a result, these applications are susceptible to be undermined by factors outside of what is measured and modeled (Brynjarsdóttir et al. 2012) and outside of what can realistically be measured and modeled. Another potential problem is that society tends to measure what people care about, and those measurements alter what people believe is important; particularly problematic is that people tend to overrate the importance of what is salient, tangible and familiar at the expense of delayed and distant less tangible effects (Sterman 2002). The risk thus is that society confuses resource management with the complex problem of sustainability. Furthermore, Brynjarsdóttir and colleagues (2012) point out that focusing on simple metrics may sidestep more difficult lifestyle choices that may be required to make society more sustainable. Similarly, Strengers (2011b) argues that focusing on simple metrics overlooks the practices householders engage in and take for granted, and that efficiency gains can easily become offset by the adoption of new resource-consuming expectations and desires. To overcome these limitations, Strengers (2011b) and Brynjarsdóttir and colleagues (2012) advocate a shift towards a focus on everyday life and everyday practices, consisting of three central aspects: promoting reflection on what it actually means to be sustainable, negotiating needs and consumption limits, and promoting new practices which challenge taken-for-granted notions of normality.

4.3. Limitations of Optimization

The reduction of sustainability to resource management described by Brynjarsdóttir and colleagues (2012) resembles what Sterman (1991) describes as optimization model, the output of which is a statement of the best way to accomplish some goal. An optimization model typically includes three parts: an objective function specifying the goal or objective; the decision variables representing the choices to be made; and the constraints restricting the choices of the decision variables to those that are acceptable and possible (Sterman 1991). One of the difficulties with optimization models pointed out by Sterman (1991) is the problem of specifying the objective function, that is, the goal that the model user (in our case society) is trying to reach. In a consumer capitalist society relying on ecological modernization strategies, the overarching objective function normally is economic growth. In this context, it is not surprising that most approaches to sustainability aim at maintaining growth through technological innovation and greater material and economic efficiency (i.e. optimization). Rees (2009) argues that these approaches are ill-conceived and largely ineffective, as they ultimately aim to allow more people to increase their consumption and thus do not address the fundamental problem. Blühdorn (2007) provides a similar argument and contends that most approaches to sustainable development tackle symptoms but never address the root causes of environmental decline. Rees (2009) suggests a complete reexamination of society's relationship with nature in order to achieve sustainability.

Hargreaves (2012) contends that much current research into pro-environmental behavior is misguided, even potentially dangerous, since it has predominantly focused on analytical rationality (episteme) and the application of technical skills and knowledge (techne); instead, pro-environmental behavior research should be oriented towards seeking answers to a range of broader value-rational questions focusing on the operation and interplay of values and power in specific settings, thereby ensuring the ethical employment of science and technology (phronesis). Similarly, Danilov-Danil'yan and colleagues (2009) suggest that progress towards sustainability requires significant individual moral development leading to a "collective moral renewal".

4.4. Limitations of Rationality

Menzel (2013) suggested that dual-process models known from cognitive psychology and neuroscience (Evans 2011) are more appropriate to understand and foster sustainable decision-making than the more rationalist models commonly used in ecological and behavioral economics. In dual-process models decision-making is seen as a result of two systems: one is described as affective, associative or experiential; the other is described as deliberative or analytical (Menzel 2013).

If such a dual-process model is adopted, four explanations of unsustainable behavior can be found according to Menzel (2013): contra-sustainable intuitions that are stronger than pro-sustainable reasoning; strong contra-sustainable intuitions and weak or inexistent pro-sustainable intuitions; the benefits of contra-sustainable choices are greater than the benefits of pro-sustainable choices (this is the only explanation in the established economic model); pro-sustainable intuitions that are weaker than contra-sustainable reasoning. In order to address and mitigate all four possible reasons for unsustainable behavior, Menzel (2013) suggests a number of complementary policies: fostering pro-sustainable emotions; limiting the promotion of counter-sustainable intuitions; questioning strong contra-sustainable reasoning; changing default choices; and education about the influence of emotions on decision-making.

4.5. Limits of the Current Sustainability Narrative

Dobson (2000) identified two strands of environmental thought: environmentalism (i.e. managerial approach to environmental problems, which are assumed to be resolvable without fundamental changes in present values or patterns of production and consumption) and ecologism (i.e. proposition that a sustainable and fulfilling existence presupposes radical changes in our relationship with the non-human natural world, and in our mode of social and political life). These two discourses on sustainable development were analyzed in depth by Urhammer and Røpke (2013), who provided a mapping of two main responses (narratives) to the current environmental, economic, and social crises: the pro-growth narrative starts from business as usual and seeks to establish a green growth economy through system modification; the no-growth narrative starts from a system in crisis and seeks to establish a no-growth economy through system transformation, alternative ownership and better progress indicators (Reichel 2013). Karlsson (2007) argues that the two strands, perspectives, or narratives of sustainable development in fact span a whole spectrum of different ontological assumptions, risk assessments, and preferred remedial strategies. Upon closer examination, many of the previous critical voices appear as critique of the pro-growth narrative rather than of the specific research fields or tools applied at the interface of household metabolism.

5 Conclusions and Outlook

Household metabolism is a concept that is concerned with the analysis of stocks and flows of energy, matter, and information at the household scale. The concept of household metabolism also encompasses environmental impacts resulting from resource exploitation and waste management related to household consumption. As presented in this review, the concept of household metabolism links several research fields at the interface of household metabolism that seek to make important contributions to reducing the rate of household metabolism (Table 1). Advances in any of these fields potentially support a better understanding of household metabolism.

Economic and marketing sciences provide continuously developing models of the consumption process. Newly arisen disciplines, such as neuroeconomics and behavioral economics, are fields that can greatly contribute towards improving models of the context of consumption. Due to the fast growing interest in socio-economic metabolism research, the tools to analyze the metabolism of different societal units are continuously improving. Here, the availability of geo-referenced data may offer a particularly promising opportunity for the examination of material flows and the drivers of consumption with a high spatial and temporal resolution. The household level also lends itself to the observation of consumer practices. When it comes to the *in situ* observation of individual and household consumption, consumer practices, and resource management, recent developments in ICT may be highly valuable (e.g. living labs, eco-feedback and persuasive technology). Household metabolism, as a conceptual framework, in its extended interdisciplinary interpretation, is also able to advance the understanding of complex social phenomena that may hamper efforts towards a sustainability transition, such as rebound and lock-in effects.

As a result of the use of advanced tools, such as bottom-up household MFA, living labs, or data mining, several research areas have the potential to improve the quality of description of household metabolic data, and the effect of interventions on the rate of household metabolism. However, there are a number of theoretical limitations to the effectiveness of research at the interface of household metabolism. Key limits to the potential effectiveness of research at the interface of household metabolism in improving environmental performance include the problems associated with an individual's capacity to change given her decision context (both with respect to the technical system she finds herself in, and the economic system), the limits to measurement and persuasion, and limits to human rationality.

Adopting a dual-process model of decision-making and considering complementary policies such as those suggested by Menzel (2013) would provide one possible opportunity for further research at the interface of household metabolism. Particularly eco-feedback and persuasive technology in general could target intuition and emotion rather than reasoning, which would be in line with evidence that ambient feedback is more effective than factual feedback (Maan et al. 2011). Note that it may also be illustrative to think about how eco-feedback can be obtained through non-technical means, for instance through more local supply chains where environmental and social impacts are more tangible and visible to consumers. Another interesting research direction would be to investigate whether new policy suggestions or new influence strategies such as participative communication (Dupré 2014) actually yield the desired effects in terms of reduced consumption and waste generation. This could for example be investigated in a living lab setting.

The broad variety of research fields relating to the concept of household metabolism in one way or another, and the diverse opportunities for further research, come as no surprise given the multiple roles of households. The multiple roles of households at the same time also imply that households are exposed to a variety of driving forces that all influence the rate of household metabolism in one way or another, which raises the question to which extent different driving forces are aligned with one another. Upon closer examination, it appears that many of the theoretical limitations to research at the interface of household metabolism point towards the lack of such alignment. In other words, efforts towards expressed societal goals (i.e. reduction of resource consumption and waste generation) may be thwarted by enacted system dynamics (i.e. implicit dynamics of the socio-economic system). Such misalignment could also be said to reflect a paradoxical society, which on the one hand puts enormous efforts into achieving goals such as reducing pressure on the environment, increasing human equity, and improving well-being, whilst on the other hand frenetically adhering to an economic and financial system whose internal dynamics undermine these very goals by (implicitly) promoting the opposite effects.

The concept of household metabolism can stimulate a reflection on household consumption and the (possibly contradictory) influence of different driving forces on the rate of household metabolism. In light of the multiple roles of households and the variety of research fields at the interface of household metabolism, we believe that the concept of household metabolism can be very valuable in diagnosing misalignments between enacted system dynamics and expressed societal goals, and in informing attempts towards their alignment. For example, embedding household metabolism in a multi-scale perspective has the potential of revealing inconsistencies between a desired situation (in terms of type and magnitude of flows) as formulated at the household level and the corresponding flows as implied by the structure and dynamics of higher-level scales. Hopefully the increased exposure to the research fields at the interface of household metabolism provided by this article and those it cites will provide inspiration and new ideas to challenge the limitations and bring research related to the concept of household metabolism to its full potential.

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Figures

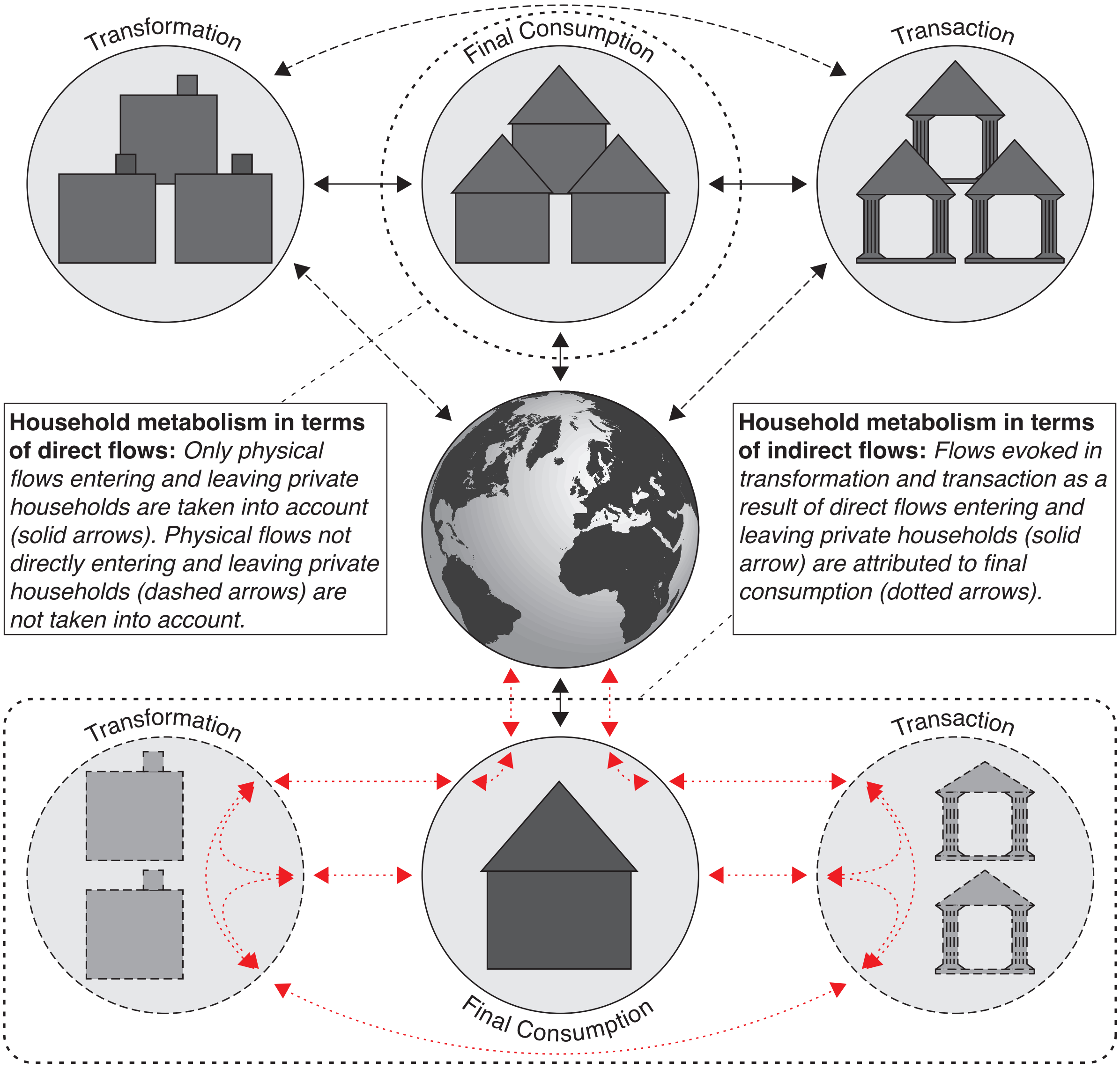

Figure 1: Conceptual model of household metabolism. Goods and services consumed by households (the socio-economic entities associated with final consumption) are provided by the socio-economic entities associated with transformation (agriculture, forestry, industry) and transaction (services and governmental institutions). Transformation refers to basic manufacturing activities, while transaction includes allocation, trading, and regulation of the goods manufactured in the transformation section. Household metabolism can encompass direct flows only (see upper half of the illustration), or it may also include indirect flows (see lower half of the illustration).

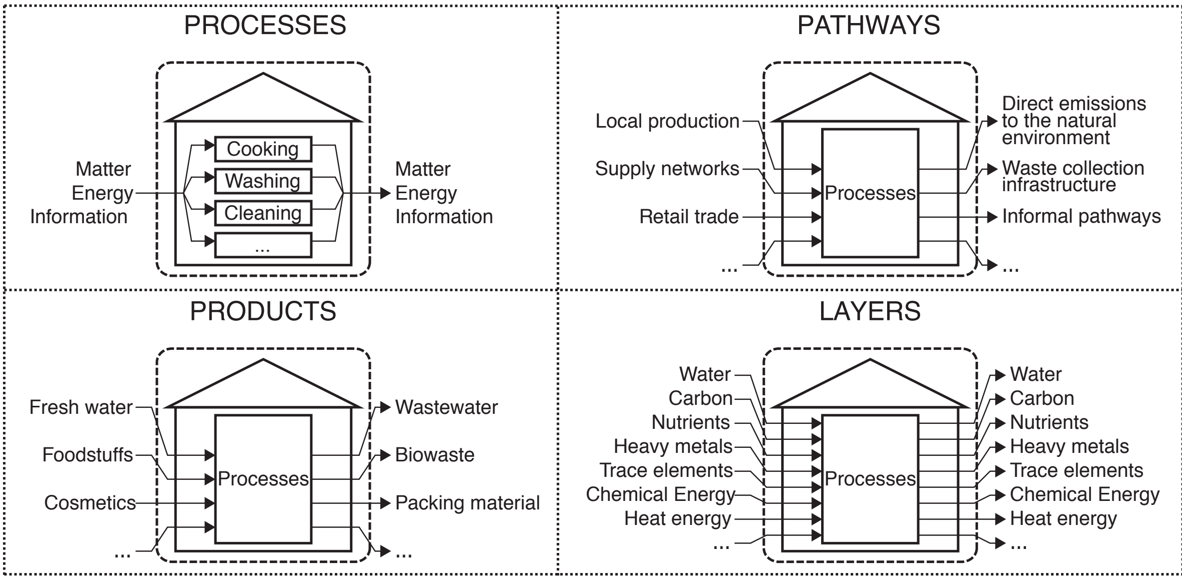

Figure 2: Household metabolism can be analysed per process, pathway, product, or layer.

Tables

Table 1: Contributions of different research fields with relevance to household metabolism.

Research Field	Contributions
Industrial Ecology	Concept of household metabolism, household metabolism as sub-domain of socioeconomic metabolism. Methodological frameworks and tools (MFA, LCA, IO analysis). Multi-scale perspective.
Social Sciences (economics, marketing, psychology, sociology)	Economic model of household consumption. Behavioral aspects of consumption and decision-making processes. Consumption patterns and trends.
Living labs	Platform for developing and testing innovations at the level of individual households.
Sensing and metering, persuasive technology	Methods and tools for quantifying and managing material flows at the level of individual households. Stimulation of behavioral change.
Practice theory	Co-management of resources, practice-oriented design.

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