BENCH.v2 agent-based model description (ODD protocol)

Guiding Protocol		BENCH model
A. Overview	**A.1. Purpose**	The *BENCH.v2* agent-based model is designed and developed to study shifts in residential energy use and corresponding emissions driven by behavioral changes among heterogeneous individuals. This empirically grounded model is of interest to (i) environmental scientists interested in modelling human behaviour and economic institutions, (ii) energy economists working on micro aspects, (iii) scholars integrating individuals behavioural change in climate change mitigation modelling.
	A.2. Entities, state variables and scales	Agents (individuals) in *BENCH.v2* model are heterogeneous in socio-demographic and dwelling characteristics, energy consumption and patterns, source of energy and energy provider, and behavioral factors. The *BENCH.v2* simulations 1383 individual households in the Overijssel provinces over 14 years (2016-2030), see Figure 4 One time step represents one round in the behavioral experiments. Each run consist of 14 time steps aligning to the 14 rounds in the behavioral experiments.
	A.3. Process overview	One time step represents one-year. In each time step: 1. Behavioral process: • Knowledge activation • Motivation • Consideration 2. Calculate utilities 3. Pick an action or not 4. Calculate saved energy and CO_2 emission 5. Social dynamics and learning process 6. Satisfaction and regret 7. Updates See Figure 2 for algorithm in the *BENCHv.2* agent-based model and Figure 1 for details on the behavioural process.
B. Design concept	**B.1 Theoretical and Empirical background**	In application to environmental- and energy-related choices, three behavioral change theories are commonly applied: theory of planned behavior (TPB), norm activation theory (NAT), and value–belief–norm (VBN) theory. • TPB, formulated by Ajzen (1980) and based on the theory of reasoned action, is one of the most influential theories in social and health psychology and has been used in many

		environmental studies (Armitage and Conner 2001; Onwezen et al. 2013). • NAT, originally developed by Schwartz (1977), operates in the context of altruistic and environmentally friendly behavior. It is mostly focused on anticipating pride in doing the "right" thing and on studying the evolution of feelings of guilt. • VBN theory (Stern 2000; Stern et al. 1999) explains environmental behavior and "good intentions" such as willingness to change behavior (Nordlund and Garvill 2003; Steg and Vlek 2009; Stern et al. 1999), environmental citizenship (Stern et al. 1999), and policy acceptability (De Groot and Steg 2009; Steg et al. 2005).
	B.2. Individual decision making	We introduce a framework that combines the strengths of the three key behavioral theories, see Figure 1.
	B.3. Heterogeneity	Agents are heterogeneous in respect of the following variables, see Table 1: • Socio-demographic • Dwelling • Energy consumption • Energy provider • Behavioral factors
	B.4. Interactions, social dynamics and learning	Agents (heterogeneous individuals) engage in interactions and learn from each other. In particular, they can exchange information with neighbors, which may alter own knowledge, awareness, and motivation regarding energy-related behavior. We employ a simple opinion dynamics model assuming that each agent interacts with a fixed set of nearby neighbors. Agents compare values of their own behavioral factors – knowledge, awareness, and motivation – with those of their eight closest neighbors, and adjust their values for a closer match, see Figure 3.
	B.5. Spatial scale	Lowest scale: Individuals Highest scale: Overijssel provincein The Netherlands (NUTS2: NL21), see Figure 4.
	B.6. Individual prediction	Individuals do not predict future condition.
	B.7. Stochasticity	There are various sources of stochasticity in the model: 1. Initial setting: Agents attributes (initialization are partly random) 2. During the process: Social dynamics and learning (process is partly random)

	B.8. Observation	*BENCHv.2* estimates cumulative impacts of energy-related behavioral changes of individual households on electricity consumption and CO_2 emissions. Reports: • Number of energy-related actions per year: investment, conservation, switching • Saved electricity per action/year: investment, conservation, switching • Avoided CO_2 emission per action/year: investment, conservation, switching
	B.9. Implementation Details	The model is coded in Netlogo 6.0.4, Open source and available on CoMSES (https://www.comses.net) R is used for the result visualizations.
C. Details	**C.1. Initialization**	The variations in socio-demographic, dwelling and psychological factors among our survey respondents are used to initialize a population of heterogeneous agents in the *BENCHv.2* model.
	C.2. Input data	The data on the behavioral and economic factors affecting household energy choices were collected using an online questionnaire (N= 1383 households in Overijssel) and serve as empirical micro-foundation of agent rules in the *BENCHv.2* model.

Figures

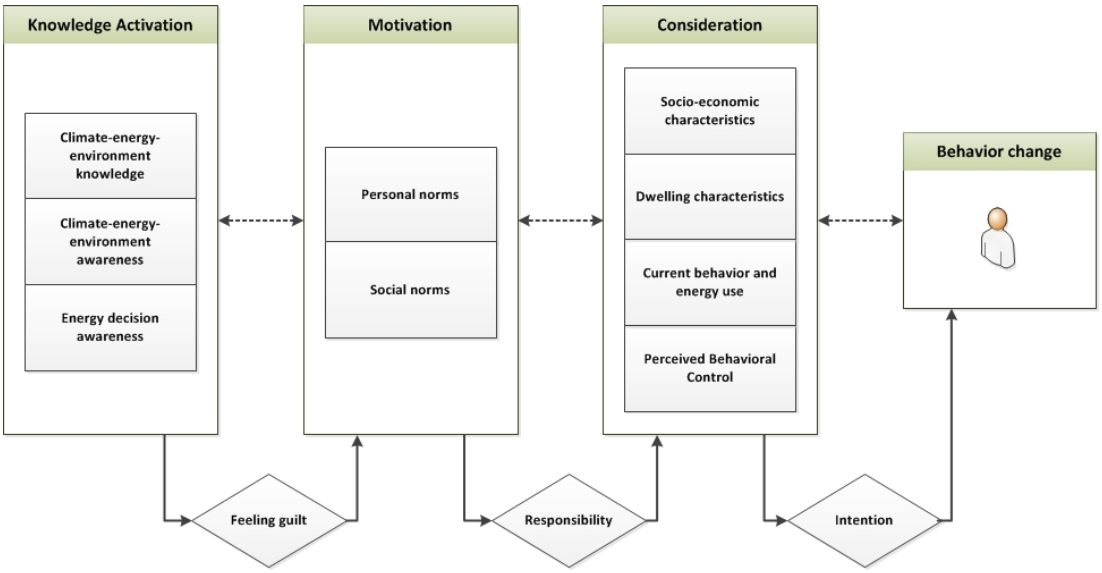

Figure 1: *BENCH* conceptual framework

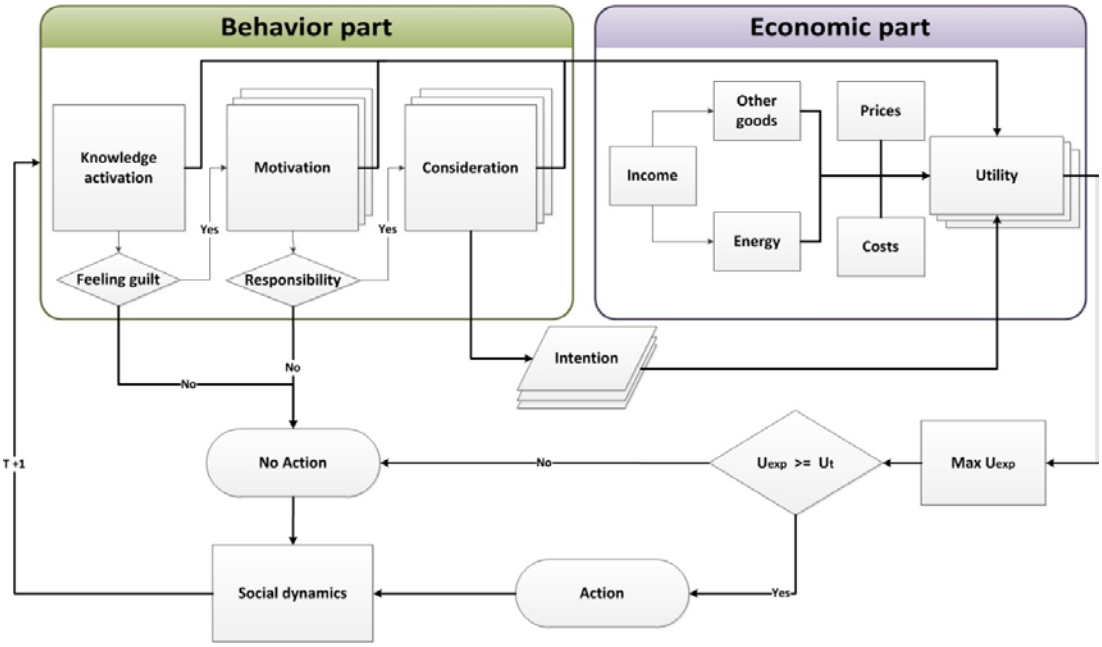

Figure 2: An agent's decision-making algorithm in the *BENCHv.2* agent-based model

Figure 3: Social dynamics and learning in an active neighborhood where household “5” undertook an action at time t. (a) Slow dynamics: households 3 and 4 are affected and engage in social learning. (b) Fast dynamics: all households in the neighborhood are affected and engage in social learning

Figure 4: Survey case study: Overijssel province-The Netherlands

Tables

Table 1: Overview of main variables and parameters used in *BENCHv.2*

Factors	Variables	Value range
Socio-demographic	income	[1000- 150,000]
	education	[Primary-Doctoral]
Dwelling	energy label	[A-F]
	ownership status	[owner-renter]
Energy	consumption	[500-5000]
	Provider	grey, brown, green
	energy saving habit	[0-3]
Behavioral	knowledge	[1-7]
	cee awareness	[1-7]
	ed awareness	[1-7]
	personal norms	[1-7]
	social norms	[1-7]
	intention A1	[1-7]
	intention A2	[1-7]
	intention A3	[1-7]

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