Socio-Economic Energy model for Digitalization (SEED)
ODD protocol

Stermieri L.[a], Kober T.[a], McKenna R.[d,e], Schmidt T.J.[b,c] , Panos E. [a]

[a] Paul Scherrer Institute, Laboratory for Energy Systems Analysis, Energy Economics Group, Forschungsstrasse 111, 5232 Villigen PSI, Switzerland
[b] Paul Scherrer Institute, Research Division Energy & Environment, Forschungsstrasse 111, 5232 Villigen PSI, Switzerland
[c] ETH Zurich, Laboratory of Physical Chemistry, 8092 Zurich, Switzerland
[d] Paul Scherrer Institute, Laboratory for Energy Systems Analysis, Forschungsstrasse 111, 5232 Villigen PSI, Switzerland
[e] ETH Zurich, Chair of Energy System Analysis, Institute of Energy and Process Engineering, Dep. of Mechanical and Process Eng., Clausiusstrasse 33, 8092 Zurich, Switzerland

This is part of the published paper "Impacts of digitalization and societal changes on energy transition: a novel socio-techno-economic energy system model" by Stermieri et al. submitted to Energy Strategy Reviews and available as pre-print at SSRN: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4480812.

The following paragraph presents the ODD protocol [1, 2] for the SEED model.

Contents

1. Purpose of SEED 2
2. State variables and temporal and spatial scale of SEED 2
   2.1. Agents 2
   2.2. Environment 4
3. Process overview and scheduling of SEED: 5
4. Design concepts 7
   4.1. Objectives and Adaptation 7
   4.2. Prediction 8
   4.3. Interactions and learning 8
   4.4. Stochasticity 9
   4.5. Observations (Outputs) 10
   4.6. Emergence of behavior 10
5. Initialization 10
   5.1. Agents 10
   5.2. Environment 12
6. Input for SEED 12
   6.1. Input for digitalization 12
   6.1. Input from coupling with STEM 13
7. Submodels 13
   7.1. Decision-making process of households 13
   7.2. Decision process of Sub-sectors and Industry 13
   7.3. E-services adoption from Sub-sectors 13
   7.4. Interactions 13
   7.5. Output 13
   7.6. Update exogenous attributes for the next time step 13

1. *Purpose of SEED*

The model's purpose is to quantify digitalization's impact on technology investment choices, energy consumption and emissions on different energy sectors.

SEED represents the heterogeneity of decision processes of different actors in the energy sectors (households, sub-sectors of the services sector, and industries) to analyze synergies and interactions in the adoption of low-energy consuming digital services and practices induced by digitalization (so-called spillover effects). Household adoption of new digital practices can accelerate the adoption of e-services and vice-versa from the services sub-sectors. The adoption of digital technologies by households and services sub-sectors can trigger the adoption of digital technologies for process optimization in industry. Furthermore, adopting digital practices by households changes their transport and residential energy consumption, altering their investment decisions in transport and residential technologies.

2. *State variables and temporal and spatial scale of SEED*

2.1. Agents

The model comprises several agents: Households, services Sub-sectors, Industry 2 (agents are described with capital letters). The unique attributes characterizing them are summarized in Table 1 and Table 2.

Households perform social practices to fulfill essential needs by utilizing technologies that consume energy. Households base their decisions by comparing costs, preferences, and availability of practices and technologies. However, preferences (Table 3) can be changed by interactions among Households in their social networks ("social media" and "face-to-face" networks). Households interact with Sub-sectors by working for them (employees-employer relationship) or by adopting their services (consumer-Sub-sector relationship). Sub-sector agents represent the services sector (Education, Health, Commerce, IT, Real Estate, Hospitality, Insurance, Research, Bank), and their objective is to minimize cost by considering the needs of employees and customers. By selecting the most profitable service, Sub-sectors can enable or prevent Households from performing digital practices. For example, by adopting the e-commerce service, they enable Households to perform the practice of e-shopping. The digitalization level of services Sub-sectors agents is used as a proxy for the digitalization level of the Industry sector agent, in this context the two agents exchange information on digitalization.
SEED proceeds in annual time steps covering the time period from 2020 to 2050 for Switzerland.

Table 1: The socio-economic attributes for Households are described, together with the reference dataset concerning the application for Switzerland. Adapted from [3].

Attributes	Heterogeneity of "Households"	Data source	Static/ dynamic	Domain
Income	The distribution income (Lognormal, μ= 1.3, sd= 0.6) is grouped into five groups with average incomes of: 4000 CHF/m, 4500 CHF/m, 6200 CHF/m, 8300 CHF/m,13800 CHF/m	[4]	Dynamic	CHF/month
Education	Degree secondary I, degree secondary II, degree tertiary	[5]	Static	[1:1:3]
Age	18-24,25-44,45-65	[6]	Dynamic	year
Location	Urban/ Rural	[7]	Static	0/1
Sinus-Milieus	It represents the heterogeneity of societal values and lifestyles among the population, subdivided into 10 groups.	[8]	Static	[1:1:10]
Job	12 types of jobs in different sectors	[9]	Static	[1:1:12]
List of social parameters	Environment, Comfort, Time saving, Leisure (Table 2)	[7]	Static	-
Preferences' value	To each social parameter is attributed a value from 0 to 1	[7]	Dynamic	[0,1]
Trust in information	Trust in social network and physical network	[7]	Dynamic	[0,1]
Building type	Multi-family, Single Family	[10]	Static	[0,1]
Annual mileage	Total kilometers driven per year subdivided into the type of trip (leisure, commuting, education, shopping	[11]	Dynamic	km/year
Share of expenditure	The available income is subdivided into expenditures: transport, residential, savings, and other	[12]	Dynamic	%

Universe	Represent the weight of the universe of the agent, the number of real "Households" represented by it	[10]	Static	N. households
Practices	The set of practices performed by the agent	Result	Dynamic	-
Intensity of usage of ICT technology	Intensity of usage of ICT technology (once a digital practice is adopted, the frequency of performing it from the Households increases every year by the digitalization parameter selected for the scenario analysis)	Assump tion based on [13]	Dynamic	[0,1]
Technology	Set of technology used by the agent	Result	Dynamic	-
Social network link	Number of connections in the social networks throw which "Households" exchange and update preferences	[8]	Dynamic	[1:1:7]
Residential energy demands	Heat and electricity demand connected to the building type and period	[10]	Dynamic	kWh/year

Table 2: The socio-economic attributes for Sub-sectors and Industry are described, together with the reference dataset concerning the application for Switzerland. Adapted from [3]

Attributes	Heterogeneity of "Sub-sectors"	Data source	Static/dynamic	Type of value
Job type	This attribute connects the job of Households with Subsectors: employees-employer connection	[9],[14]	Static	[1:1:12]
Gross Value Added	Gross value added is used as a proxy to evaluate the available budget of the sub sector to invest in new services	[15]	Dynamic	MCHF/year
Employees	The number of employees ("Households" agent)	[9]	Dynamic	n. of agent
Space	The office space attributed in km2	[10]	Dynamic	km2
Sub-sector end-uses energy demands	Heating, Electricity and internet data demand	[10]	Dynamic	PJ and GB
Digitalization level	The digitalization level is modeled as an s-shaped function, it uses as a proxy the intensity of adoption of a practice to evaluate the digitalization of a company	Assumption based on [16]	Dynamic	[0,1]
The intensity of adoption	The intensity of adoption of practice and related digital e-services services (average "intensity of ICT use" among their employees to evaluate at which frequency employees desire to perform the social practice associated with the e-service analyzed)	2020 statistics	Dynamic	[0,1]
Practices	Set of practices (e-services) adopted	Result	Dynamic	-
List of social parameters	List of social parameters: satisfaction of employees, satisfaction of customers, digital readiness	assumption	Static	-
Preference value	Values of social parameters	assumption	Dynamic	[0,1]
Socio-economic attribute	**Industry**	**dataset**	**Static/dynamic**	**Type of value**
Processes electricity demand	Electricity demand for industrial processes	[10]	Dynamic	PJ
Digitalization level	The digitalization level is calculated as the average digitalization level of the services sector	Assumption based on [17]	Dynamic	[0,1]

Table 3: Preferences of Households and their connection to technology choices. The social parameters of household agents (first column) are used in the preference component of the multi-criteria function of "Households" to evaluate "Households"' preferences to adopt practices and technologies. The table shows the connection between social preferences and the teleworking practice (column named P), Transport technologies (TT), Residential Heating technologies (RHT), Residential Electricity Technologies (RET) to which they refer. Adapted from [3].

	P		TT						RHT								RET	
Social parameter of household agents: preferences	Teleworking	Commuting	ICE vehicles	electric vehicles	plug in	hybrids	fuel cell	public transport	Natural gas boiler	Oil boiler	Wood boiler	District heating	Electric boiler	Electric heat pump	Natural gas heat pump	Solar thermal	Photovoltaic panel	Electricity grid
Balance between work/free time	x	x																
Free time scheduling	x	x																
Commuting distance	x	x	x	x	x	x	x	x										
Importance of time savings			x	x	x	x	x	x										
Traveling comfort			x	x	x	x	x	x										
Time for leisure activities			x	x	x	x	x	x										
Environmental awareness			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Thermal comfort									x	x	x	x	x	x	x	x		
Available space									x	x	x	x	x	x	x	x	x	x
Noise intensity									x	x	x	x	x	x	x	x		
Preference for self-consumption technologies																	x	x
ITI skills	x																	
Infrastructure anxiety	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x		
Satisfaction as employee																		
Satisfaction as costumer																		

2.2. Environment

The environment contains variables related to time, social networks, practices and technologies which are fixed (or variate dynamically in a pre-define way). The variable related to digitalization and that provide different scenarios are also included. Table 3 shows the state variables of the environment.

Table 4: Assumptions used to simulate technologies, practices, and business models. Additional information are provided in the Supplementary material of this thesis.

	Transport technologies for Households	Dataset	Static/ Time Dynamic	Type of value
Type	ICE private vehicle, EV private vehicle, plug-in private vehicle, hybrid private vehicle, fuel cell private vehicles	[18]	Static	-
Technical attributes	CAPEX, OPEX, efficiency, lifetime, discount rate	[18]	Dynamic	CAPEX: CHF/technology, OPEX: CHF/year, efficiency: km/GJ, lifetime: year, discount rate: %
Non-technical attributes	Environment, Comfort, Time saving, Leisure	Assumptions	Dynamic	[0,1]
	Residential technologies for Households			
Type	Natural gas boiler, oil boiler, wood boiler, electric heat pump, natural gas heat pump, district heating, electrical resistance heater, solar photovoltaic panel	[18]	Static	-
Technical attributes	CAPEX, OPEX, Efficiency, Lifetime, Discount rate	[18]	Dynamic	CAPEX: CHF/KW, OPEX: CHF/year, efficiency: kWh/GJ, lifetime: year, discount rate: %
Non-technical attributes	Environment, Thermal comfort, Noise, Space	Assumptions	Dynamic	[0,1]

	Electrical appliances (Households, Sub-sectors, Industry)			
Type	Conventional, smart	[19]	Static	-
Technical attributes	CAPEX, OPEX, Efficiency, Lifetime, Discount rate	[19][1] [20][2]	Dynamic	CAPEX: CHF/technology, OPEX: CHF/year, efficiency: kWh/ technology, lifetime: year, discount rate: %
Non-technical attributes	IT skills	Assumptions	Dynamic	[0,1]
	Practices for Households			
Type	Digital: teleworking, e-commerce, smart thermostat, smart meters and IT feedback (digital device that provides feedback on energy consumption) Conventional: going to work, shopping		Static	-
Technical attributes of digital practices	*Teleworking*: commuting reduction, Number of hours as video-conferencing, Internet data demand, Change in residential heating demand, Change in residential electricity demand *E-commerce*: commuting reduction, increase in van deliveries *Smart thermostat, smart meters and IT feedback*: Energy saving potential of smart technologies in residential	[21] [22] [23, 24]	Dynamic	commuting reduction: km/remote working day, Number of hours as video-conferencing: hours/remote working day, Internet data demand: GB/year, Change in residential heating and electricity demand: % increase in van delivery: km/adoption of e-commerce
Non-technical attributes	*Teleworking/Commuting:* work/life balance, opportunity to freely organize when and where to work, distance, IT skills *E-commerce/shopping:* work/life balance, distance, IT skills *Smart thermostat*: willingness to save heat, willingness to change habits, IT skills *Smart meters and IT feedback*: willingness to save electricity, willingness to change habits, IT skills	Assumption	Dynamic	[0,1]
	e-services for Sub-sector			
Type	Remote work, e-commerce, e-learning, e-banking		Static	-
Technical attributes	*E-commerce*: ICT for optimizing transport logistics, Energy saving potential when connected to smart technologies in offices *Remote work*: Energy saving when connected to smart technologies in offices	[25], [26], [27], [28], [29], [30]	Dynamic	%
	Digitalization input for scenarios			
Increase of Intensity of ICT use	the intensity of digital practice among the population (representing the digital readiness of the population), increase per year	Based on scenario	Static	(%/year)
Increase of ICT budget	the budget of companies attributed to ICTs investment, increase per year	Based on scenario	Static	(%/year)
Increase of Digital job probability	the probability of having a digital job for the newly-entered Households agent (representing the role that government plays in creating more digital-intensive jobs), increase per year	Based on scenario	Static	(%/year)

[1] **Households and services Sub-Sectors,** [2] **Industry.**

3. *Process overview and scheduling of SEED:*

Processes are grouped into six main steps, and within each year, they are processed in the order described in Figure 9: decision-making process of Households agents, the decision-making process of services Sub-Sectors agents and Industry sector agent, e-services adoption, interactions of Households, obtained model outputs, and update of exogenous input variables for next time step. Within the decision-making process of Households, Households select the practices (random order) and then the technology (transport, residential, electrical appliances). Within each process, agents are simulated in random order. The scheduling of the processes is decided following the idea that the decision of Households impacts the decision of Sub-sectors (and vice versa), which influences the decision of Industry.

Process overview and scheduling of SEED

Initialization phase: t=2020

Initialize time horizon $t \in T, T = \{2020, 2021, 2022, \ldots, 2050\}$
Initialize synthetic population of Households, Sub-sectors services and Industry sectors, building stock (*ODD,* section e)
Import exogenous inputs *(ODD, section f*):
Input for digitalization, Input for socio-economic structure, Input from coupling with STEM

For each year t **do**: (*ODD,* section g)

Decision-making process of households:
For each Households **do**:
Decide on the adoption of social practices (digital vs conventional)
Decide to invest in transport and residential technology
Update energy technology stock if new investment
Update expenditure if new investment
Update energy consumption and demand
End

Decision-making process of Sub-sectors services and Industry sectors:
For each sub-sector services agent and industry agent **do**:
Decide on the adoption of electrical appliances
Update energy demand if a new appliance is adopted
Update digital level if a smart technology is selected
End

Decision-making process for e-services:
For each sub-sector services agent **do**:
Decide on the adoption of e-services
Update digitalization level of sub-sector if e-service is selected
Spillover effects between Households and Sub-sector
Update energy consumption
End

Interaction of Households:
For each H*ouseholds* **do**:
Interaction in social networks to update social values and preferences
End

Output: *(ODD, section d)*
Energy-system related output:
Socio-economic output:
Energy-technology related output
Households-related output

Update exogenous attributes for next time step: (*ODD, section g*)
Demolish/Build building stock
Ageing of population, introduction of new Households
Update income of households based on GDP evolution
Increase intensity of ICT use, ICT budget for firms, population with digital jobs.

End

Figure 1: The process overview and scheduling of SEED as depicted in the ODD protocol are provided. Adapted from [3].

4. *Design concepts*

4.1. Objectives and Adaptation

Households objectives:

Households aim to select the social practices that best fit their preferences (in terms of social attributes and economic considerations). They can choose between conventional and digital practices. The decision is based on the maximization of a multi-criteria function with four components:

- agents' preferences: the preference of the Households are compared with the attributes of the practice to seek the closest match (Table 4).
- the cost of the practice: investment and operational cost associated with the energy technology (or, technologies) needed to perform the practice.
- Infrastructure access anxiety: (if applicable to the chosen practice) the infrastructure to support the chosen practice should be available to the Household agent. For digital practices, internet infrastructure is needed to be in place.
- Social diffusion of the practice: number of Households in its social network which perform the practice

The decision to adopt a practice is limited by the Sub-sector agent that needs to support it too. In particular: teleworking is limited by the adoption of the Remote-work model by the Sub-sector representing the employer of the Households; E-commerce is limited by the adoption of e-commerce e-service by the Sub-sector representing the Commerce sub-sector. Households decrease their satisfaction level connected to the Sub-sector (satisfaction as costumer and satisfaction as employees, Table 2) if the practice is not supported from that Sub-sector.

In each time step Households can decide to adopt a different practice. If a digital practice is selected, "the intensity of using ICT", representing the frequency to which the digital practice is performed (teleworking= days per week, e-commerce= share of online shopping over total shopping), increases in every time step. The increase depends on the input parameter (increase in "ICT intensity use", annual increase in ICT budget for Sub-sectors, probability of having a job that can be performed digitally, see input parameter for digitalization).

Households aim to select the residential and transport technology to fulfill their needs (for traveling, heating the apartment, and using electrical appliances) that best fit their preferences (in terms of social attributes and economic considerations (Tables 3 and 4)). They can choose between five transport technologies, seven residential technologies, and two electrical appliances (Table 4). The decision is based on maximizing a multi-criteria function with four components, similar to the ones described for the practice choice (i.e., preference, cost, infrastructure access anxiety and diffusion of the technology in the market).

The decision is limited by the available budget for the investment in the specific technology and by the availability of the infrastructure. For example, district heating and natural gas cannot be selected if the infrastructure is not available for the Households.

When Households replace existing equipment before its lifetime, e.g., because of the change in the practice or because investing in a new technology is more cost effective than operating the existing one, the annual capital expenditures of the existing equipment are still paid until the capital cost of the existing equipment is fully recovered.

Services Sub-sectors and Industry objectives:

Service Sub-sectors aim to adopt the service that shows the minimum cost. They can choose between conventional and digital services (e-service). The cost function depends on:

- the available budget to invest in ICTs (for e-services)
- the energy cost associated with the service
- additional cost (cost to replace unsatisfied employees quitting their job, renting cost for offices)

Sub-sectors are limited in the adoption of an e-service by the number of employees (Households working for them) or consumers (for the Commerce sector) that “want” to perform the digital practice connected to the e-service (teleworking and e-commerce) (Households might not be allowed in the end if the Sub-sector does not support the practice) and by the average “ICT intensity of use”, which determines how often, on average, Households would have liked to perform the practice.
Each year, Sub-sectors can decide to increase the allowed intensity for each practice, increasing their digitalization level.
Sub-sectors and Industry aim to adopt the electrical appliances that best fit their preferences (in terms of digital and energy cost). They can choose between conventional and smart electrical appliances. The decision is based on the maximization of a multi-criteria function with two components:

- agents' preferences: the preference of the agents for digitalization are compared with the attributes of the technology to seek the closest match
- the cost of the technology: investment and operational cost of the technology

4.2. Prediction

Agents do not have a future vision and make decisions based on the current information for each time step.

4.3. Interactions and learning

Households:
The learning process of Households occurs through interactions in “social media” and “face-to-face” networks. Through interactions in social networks, Household agents modify their preferences for practices and technologies over time. In the face-to-face network, Household agents interact within their neighborhood and working space. It is a simulation of the physical interactions between the agents, which is constrained by their spatial proximity. In the social media network, the spatial proximity constraint is lifted, but the update of the preferences is weaker than in the physical case. The interactions between Households follow an opinion dynamics model with asymmetric confidence [173] to simulate their learning process. A Household interacts only with the other Households in its social networks whose preferences “differ from his own not more than a certain confidence level” [173]. The confidence level, ranging from 0 to a positive upper bound, depends on the trust of the received information and shapes the ability of a Household to change its preferences. The speed of this change (learning speed) and the number of links between Households in both social networks depends on the Sinus-Milieus® of Households [8]. The links are associated with probabilities for their creation and destruction (see input section f).

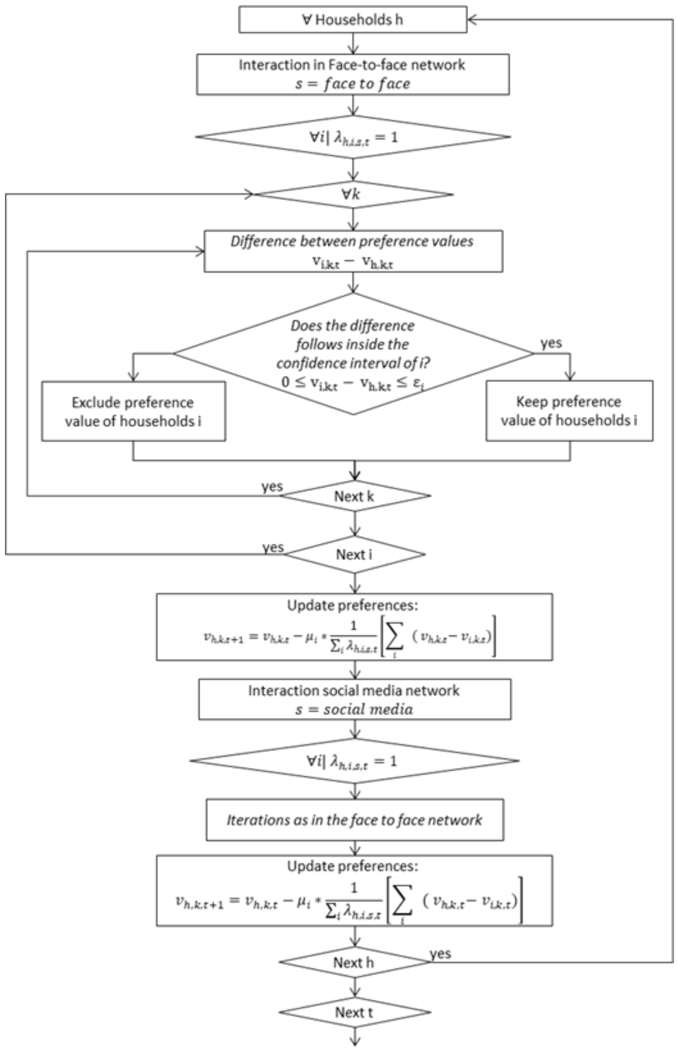

Figure 2: Interactions of Households in their social networks. Adapted from [3].

Services Sub-sectors:

Sub-sectors agents evaluate the satisfaction level of their employees and consumers. A lower satisfaction level is translated into additional cost from quitting. Sub-sectors consider the average "intensity of ICT use" among their employees to evaluate at which frequency employees desire to perform the social practice associated with the e-service analyzed (teleworking or e-commerce).

Industry:

The Industry agent evaluates the average digitalization level among Sub-sectors and changes its preference for investing in smart electrical appliances. The rationale for this is that industry does not stay behind in the digitalization of its processes compared to the rest of the economic sectors and households.

4.4. Stochasticity

The evolution of society and social attributes (such as income and age) over time are stochastic. The evolution of the building stock, the creation of links in the social network, and the introduction of new households (and their socio-demographic attributes), are based on probabilities distributions provided as input parameters.

4.5. Observations (Outputs)

The following types of results can be collected from the SEED simulation:

- Energy demand-related output for Switzerland: private cars transport demand (billion vehicles kilometers), public transport demand (billion vehicles kilometers), light vehicles freight transport demand (billion vehicles kilometers), residential heating demand (PJ), residential electricity demand (PJ), tertiary sector heating demand (PJ), tertiary sector electricity demand (PJ), internet data demand (GB), and industrial electricity demand (PJ).
- Energy technology-related output for Switzerland:
  - Transport (Million vehicles): ICE private vehicle, EV private vehicle, plug-in private vehicle, hybrid private vehicle, fuel cell private vehicles
  - Residential (PJ): Heat supplied from Natural gas boiler, oil boiler, wood boiler, electric heat pump, natural gas heat pump, district heating, electrical resistance heater, solar photovoltaic panel
- Socio-economic output: adoption of social practices by households, which is reported as a share of households adopting the practice over the total number of households (going to work, teleworking, shopping, e-shopping, use of thermostat, electricity saving feedback, renovation measures).
- Households-related output: socio-demographic attributes that change during the SEED simulation (as listed in Table 2), practices adopted (yes or no), transport technology adopted (type), residential technology adopted (type), economic expenditures (transport, residential, savings in CHF per year)

4.6. Emergence of behavior

The energy demand-related and socio-economic output result from the adoption of digital practices and business models by Households, services Sub-sectors, and Industry agents, and the operation patterns of the technologies used to perform these practices. The energy technology-related outcome results from the investment decision of Households.

5. Initialization

5.1. Agents

A synthetic population approach [31] is applied to simulate the households of Switzerland and ensures statistical equivalence with the real Swiss population, similar to the approach of Panos et al. [8].
The synthetic population of agents is based on a Latin hypercube sampling [32] using joint probability distributions fitted to aggregated socio-demographic data (Table 5, Table 6).

Table 5: Distribution of socio-demographic attributes used to create the synthetic population for Switzerland

Attribute	Description	Data source	Distribution
Age	18-24,25-44,45-65	[6]	Multinomial
Income	Five groups with average incomes of: 4000 CHF/m, 4500 CHF/m, 6200 CHF/m, 8300 CHF/m,13800 CHF/m	[4]	Lognormal, μ= 1.3, sd= 0.6
Education	Degree secondary I, degree secondary II, degree tertiary	[5]	Multinomial
Households type	With children/ without children	[33]	Multinomial
Sinus-Milieus	It represents the heterogeneity of societal values and lifestyles among the population, subdivided into 10 groups.	[8]	Multinomial

Table 6: correlations between different socio-demographic attributes to create the synthetic population for Switzerland [34], [35], [8]

	Age	Education	Household type	Income	Sinus-Milieus
Age	1	0,5	0,62	0,99	-0,3
Education	0,5	1	0,34	0,99	0,94
Household type	0,62	0,34	1	1	0
Income	0,993	0,99	1	1	0,88
Sinus-Milieus	-0,3	0,94	0	0,88	1

The Swiss Household Energy Demand Survey (SHEDS) [7] is used to identify lifestyle needs and preferences. These attributes are matched with socio-demographic attributes (income, age group, education) to initialize the synthetic population (Table 7). Furthermore, each Household is randomly initialized to a specific age within the boundary of its age group. The initial number of Household agents is 441 and evolves over time based on the assumed demographic growth and household size. Additionally, a normal distribution is fitted to the Microcensus 2015 [11] to attribute to each Household a heterogeneous share of annual kilometers driven for commuting, shopping, education, and leisure activities.

Table 7: Example of how attributes from SHEDS [7] are used to initialize the synthetic population

Matching socio-demographic attributes		Lifestyle needs and preferences from SHEDS			
Households (synthetic population)	Households SHEDS	Preference	Measuring	Matching question(s) in SHEDS	Translation to numerical value [0,1]
Income = 3 Age =2 Education= 1	Income =3 Age=2 Education=1	Environment	Environmental awareness	“Planning to reduce your carbon footprint” (psy8 1019), [1,5]	Env= psy8 / 5
		Trust in information	Trust attitude	“Regarding energy and saving energy, how strongly do you trust information provided by the following people?” (Soc6 2017)	Trust= soc6/5

The services sector is subdivided into eight categories following the Statistical Classification of Economic Activities in the European Community (NOGA) [14]: Education, Health, Commerce, IT, Real Estate, Hospitality, Insurance, Research, Financial sector. Each category is represented by a Sub-sector agent, characterized by its heat and electricity demand. Furthermore, it is equipped with economical attributes, such as gross value added, and social attributes representing the relationship with employees and customers (satisfaction level attributes).

The weights used in the multi-criteria functions of households' decision processes and the parameters driving their social network interactions are kept constant over time (Table 8). The SEED model's calibration was performed using the BehaviorSpace software tool provided in NetLogo [36], which allows for varying the input parameters over several simulation runs systemically and recording each run's results. A first calibration step concerns the parameters driving the social network interactions of Households: the speed of adaptation and the upper bound of the confidence level (threshold value). The calibration of these parameters is based on the “environmental awareness” preference because it is the only one available as a time series in SHEDS.

The diffusion of this preference among Households agents of SEED for the period 2016-2018 is recorded for different combinations of these two parameters, and it was compared with the diffusion identified by the respondents of the SHEDS survey over the three waves covering the same period. The absolute error between them is calculated for each combination of values, and the values resulting in the minimum error over the three years were selected. This leads to a value of 0.1 for the speed of adoption and 0.17 for the threshold value.

A similar approach has been followed to calibrate the weight parameters of the different utility functions for Households for technology adoption. In particular, the weights of the cost, preference,

infrastructure, and market components were systematically varied from 0.05 to 1 in steps of 0.05. The adoption rate of each transport and residential technology for 2010-2018 identified in SEED was then compared with the official statistics of Switzerland. The Root Mean Squared Error (RMSE) is calculated for each technology, and the combinations of parameters with the lowest RMSE are selected to initialize the weights (see Table 24). The years 2019-2021 are used to validate the model, comparing the technology adoption of SEED with the Swiss new sales dataset. The error between the real data and SEED simulation is lower than 10%.
Concerning the utility function for the adoption of teleworking, its weights are calibrated and validated using the official statistic for teleworking in Switzerland, where the number of employees performing the social practice "Teleworking" increased to 23.8% in 2018 (compared to 18.2% in 2013) [13].

Table 8: Parametrization of the weights for the multi-criteria functions of Households. For additional information on how they are calculated, the reader is redirected to the Appendix of this thesis.

	Weights of multi-criteria functions for decision process of Households	**Value**
Residential	Weight of Preference component from calibration	0.75
	Weight of cost component from calibration	0.15
	Weight of infrastructure component from calibration	0.8
	Weight of diffusion in society component from calibration	0.4
Transport	Weight of Preference component from calibration	0.75
	Weight of cost component from calibration	0.2
	Weight of infrastructure component from calibration	0.8
	Weight of diffusion in society component from calibration	0.1
Electricity	Weight of Preference component from calibration	1
	Weight of cost component from calibration	0.15
	Weight of infrastructure component from calibration	0.8
	Weight of diffusion in society component from calibration	0.4
Practices	Weight of Preference component from calibration	0.8
	Weight of cost component from calibration	1
	Weight of infrastructure component from calibration	0.5
	Weight of diffusion in society component from calibration	0.2
	Parameters of social network from calibration	
Social-network	Speed of adoption of a new preference	0.1
	Threshold value defining if two different households in their social network will interact	0.17

5.2. Environment

The building stock is represented by two types of buildings (multi-family and single-family), each characterized by eight building periods (1919, 1945, 1970, 1990, 2000, 2010, 2015, 2018) and their grid infrastructure availability (e.g., natural gas and district heating grids). It is initialized based on [37]. The evolution of the building stock is based on the survival probability assumed for each building (different according to building type and period)[10]. New buildings are built following the annual growth extrapolated by the JASM dataset [10, 38].
The social networks of households are characterized by different probabilities of creating and destroying links [66].
The population and GDP growth are based on [38], while the probability distributions of the socio-demographic attributes are the same used to develop the synthetic population in the initialization step.
The input for end-use technologies (CAPEX, OPEX, efficiencies, lifetime) comes directly from the STEM technology database [18].

6. Input for SEED

6.1. Input for digitalization

Three indicators, based on the Network Readiness Index[39], drive the evolution of digitalization in SEED: the intensity of digital practice among the population (representing the digital readiness of the population), the budget of companies attributed to ICTs investment, the probability of having a digital job for the newly-entered Households agent (representing the role that government plays in creating more digital-intensive jobs). The budget for ICTs investment constrains the decision process of Firms investing in digital business models, while the probability of having a job that can be performed digitally for the new Households agent impacts the number of "Households" that are allowed to perform digital practices in their job. The value of these indicators can be assumed in SEED to develop digital scenarios (Table 3).

6.1. Input from coupling with STEM

Evolution over the time horizon of the energy carriers long-term marginal cost (used as a proxy of the price of the energy carrier) and the energy supply infrastructure (electric vehicles charging infrastructure).

7. Submodels

7.1. Decision-making process of households

The decision of Households on which practice to adopt is based on the maximization of a weighted multi-criteria function that considers agents' preferences for social practices, the cost of the performed practice, infrastructure access anxiety, and market share of the practices (share of Households in the social network which performs the practice compared to the total number of Households in the social network of the Households).

The decision to adopt a technology is also based on the maximization of a weighted multi-criteria function, with components similar to the ones explained for the social practice function, i.e., the practice component and the market component. In this function, the cost component represents the selected technology's annualized capital and operational cost. The infrastructure access anxiety deters the agent from investing in technology if the infrastructure needed by the technology is not available. The available income of the Household agent bounds its investment decision in the optimization problem.

7.2. Decision process of Sub-sectors and Industry

The decision to adopt electrical appliances for services and industry agents is also based on the maximization of a weighted multi-criteria function, which components are preferences and cost.

7.3. E-services adoption from Sub-sectors

Sub-sectors agents decided to adopt the e-service that minimize their cost, considering the available budget to invest in ICTs, the energy cost associated with the provision of e-services, and additional cost. Sub-sectors consider the average "intensity of ICT use" among their employees to evaluate to which frequency employees desire to perform the social practice.

7.4. Interactions

Through interactions in social networks, Household agents modify their preferences for practices and technologies over time. The speed of this change (learning speed) depends on the trust of the received information and on the ability of a Household to change its preferences (according to the Sinus-Milieus® of Households). The interactions between Households follow an opinion dynamics model [82] to simulate their learning process.

7.5. Output

The outputs are discussed in section 4.5.

7.6. Update exogenous attributes for the next time step

The evolution of the building stock is based on the survival probability assumed for each building (different according to building type and period). The new Households are randomly located at an

available building based on their preference for a multi-family or single-family house. When a building is demolished, the Households living there are randomly re-allocated to another available multi or single-family building.
New agents are introduced as old Households are removed from the simulation. New household agents are introduced with statistically similar socio-demographic attributes (Age, Income, Education, Job Type, and Sinus-Milieus®) as the ones considered in the initialization phase (same distributions and same correlations between them). The new agents' preferences reflect the society's state at the time when the new agents enter in the simulation. Each preference is initialized as a random variable following a normal distribution. The probability of the new households having a job that can be performed digitally depends on the input parameter (input for digitalization).
Each simulation year, Households age by one year, and as the simulation evolves over time, the agents above 65 years are removed from the pool of agents that can decide on societal practices.
The available income of household agents followed the assumed annual GDP growth. The new Households are initialized with the available income at the time of their entrance into society.
Finally, the parameters driving the digitalization of society are used to increase the intensity of performing digital practices for Households adopting the practice and the budget available to invest in ICT technology for the next step.

Bibliography

1. Grimm, V., et al., *A standard protocol for describing individual-based and agent-based models.* Ecological Modelling, 2006. **198**(1-2): p. 115-126.
2. Grimm, V., et al., *The ODD Protocol for Describing Agent-Based and Other Simulation Models: A Second Update to Improve Clarity, Replication, and Structural Realism.* Jasss-the Journal of Artificial Societies and Social Simulation, 2020. **23**(2).
3. Stermieri, L.K.T.M.R.S.T.J.P.E., *Impacts of digitalization and societal changes on energy transition: a novel socio-techno-economic energy system model.* Available at SSRN: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4480812, 2023.
4. *Frequency distribution (net monthly wage), full- and part-time employees by wage-level class and gender* FSO Swiss Earnings Structure Survey, Editor. 2022.
5. *Degré de formation de la population résidante permanente selon le statut sur le marché du travail et la nationalité*, Federal Statistics Office (FSO), Editor.
6. *Ständige Wohnbevölkerung nach Alter, Kanton, Bezirk und Gemeinde*, Bundesamt für Statistik (BFS), Editor. 2021.
7. Weber, S., et al., *Swiss Household Energy Demand Survey (SHEDS): Objectives, Design, and Implementation*, in *Work Package 2: Change of Behavior SCCER CREST*, S. CREST, Editor. October 2017.
8. Panos, E. and S. Margelou, *Long-Term Solar Photovoltaics Penetration in Single- and Two-Family Houses in Switzerland.* Energies, 2019. **12**(13).
9. *Personnes actives occupées par sections économiques et selon la nationalité*, federal Statistics Office (FSO), Editor. 2020.
10. *JASM Data Platform*, Joint Activity Scenarios and Modelling (JASM), Editor. 2019.
11. *Tagesdistanz, Tagesunterwegszeit und Anzahl Etappen nach Verkehrsmittelklasse und Zweck - Schweiz*, Federal Statistics Office (FSO), Editor. 2015.
12. *Enquête sur le budget des ménages, 2015–2017, Revenus et dépenses des ménages selon la classe de revenu*, Federal Statistics Office (FSO), Editor. 2018.
13. *Télétravail à domicile*, Federal Statistics Office (FSO), Editor. 2022, Dataset.
14. Federal Statistical Office, *General Classification of Economic Activities (NOGA)* 2008.
15. OECD, *Dataset: Input-Output Tables (IOTs) 2021*, OECD Statistics, Editor. 2021: https://stats.oecd.org/Index.aspx?DataSetCode=IOTS_2021.
16. Holger Greif, N.K., Patrick Warnking, *Digital transformation: How mature are Swiss SMEs?* 2016.
17. Grubler, A.W., Charlie;Bento, Nuno;Boza-Kiss, Benigna;, et al., *A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies.* Nature Energy, 2018. **3**(6): p. 515-527.
18. Panos, E., et al., *An assessment of energy system transformation pathways to achieve net-zero carbon dioxide emissions in Switzerland.* Communications Earth & Environment, 2023. **4**(1).
19. Alessia De Vita, I.K., Pavla Mandatowa, Prof. P. Capros, E. Dimopoulou, S. Evangelopoulou, T. Fotiou, M. Kannavou, P. Siskos, G. Zazias, Louise De Vos, Ali Dadkhah, Guillaume Dekelver *Technology pathways in decarbonisation scenarios*, in *ASSET project*. 2018.
20. Zuberi, M.J.S.T., Anton; Patel, Martin K., *Techno-economic analysis of energy efficiency improvement in electric motor driven systems in Swiss industry.* Applied Energy, 2017. **205**: p. 85-104.

21. BFE;Bundesamt für Energie, *Infrastructure internet*, O.-B.-U. WSA, Editor. 2019: https://www.bfs.admin.ch/bfs/en/home/statistics/catalogues-databases.html.
22. Palm, J., K. Ellegård, and M. Hellgren, *A cluster analysis of energy-consuming activities in everyday life.* Building Research & Information, 2017. **46**(1): p. 99-113.
23. Meyers, R.J., E.D. Williams, and H.S. Matthews, *Scoping the potential of monitoring and control technologies to reduce energy use in homes.* Energy and Buildings, 2010. **42**(5): p. 563-569.
24. AlFaris, F., A. Juaidi, and F. Manzano-Agugliaro, *Intelligent homes' technologies to optimize the energy performance for the net zero energy home.* Energy and Buildings, 2017. **153**: p. 262-274.
25. Cano, J.A., R.A. Gómez, and P. Cortés, *ICT Validation in Logistics Processes: Improvement of Distribution Processes in a Goods Sector Company.* Informatics, 2021. **8**(4).
26. Guerin, T.F., *Policies to minimise environmental and rebound effects from telework: A study for Australia.* Environmental Innovation and Societal Transitions, 2021. **39**: p. 18-33.
27. Raumentwicklung;, A.B.f., *Schweizerische Verkehrsperspektiven 2050*. 2021: https://www.are.admin.ch/are/de/home/mobilitaet/grundlagen-und-daten/verkehrsperspektiven2050.html.
28. Bundesamt für Statistik Eurostat, *E-Commerce und E-Banking*, B.f.S. Eurostat, Editor. 2022: https://www.bfs.admin.ch/bfs/en/home/statistics/catalogues-databases.html.
29. Bundesamt für Statistik, *Bundesamt für Statistik*, BFE, Editor.: https://www.bfs.admin.ch/bfs/en/home/statistics/catalogues-databases.html.
30. GfK ; Switzerland AG Markt Monitor Schweiz, *Onlinehandelsmarkt Schweiz 2020 Version Medien*. 2021.
31. Rolf Moeckel, K.S., Michael Wegener, *Creating a Synthetic Population*, in *8th International Conference on Computers in Urban Planning and Urban Management (CUPUM)*. May 2003: Sendai, Japan, .
32. Iman, *lhsgeneral(pd,correlation,n)*. 2022, MATLAB Central File Exchange.
33. *Private households by household type and canton*, Federal Statistics Office (FSO), Editor. 2017.
34. *Distribution du revenu disponible équivalent et ratio S80/S20, selon différentes caractéristiques socio-démographiques*, Federal Statistics Office (FSO), Editor. 2018.
35. *Ausbildungsstufen der Vollzeiterwerbstätigen von 15 bis 64 Jahren nach Familientyp* Federal Statistics Office (FSO), Editor. 2010
36. Wilensky, U., *NetLogo*. 1999, Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.
37. *Joint Activity Scenarios and Modelling (JASM)*, Joint Activity Scenarios and Modelling (JASM), Editor.
38. Hirschberg, E.P.T.K.K.R.S., *Long-term energy transformation pathways integrated scenario analysis with the Swiss Times Energy Systems Model*, Joint Activity Scenarios and Modelling JASM, Editor. 2021, Paul Scherrer Institute.
39. Portulans Institute, *The Network Readiness Index 2019: Towards a Future-Ready Society*. 2019: Washington D.C., USA.