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Title Page

Pathways to carbon neutrality by 2040: Modeling a coastal-urban city nexus with blue carbon integration

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Main Document

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Abstract

Acknowledging climate change is easy; designing and implementing effective, sustainable management strategies to mitigate it is far more challenging. To reduce carbon emissions, identifying actionable levers—particularly in complex socio-ecological systems (SESs) or city nexus—is critical for policymakers. The SES approach provides a robust lens for connecting anthropogenic and natural drivers of greenhouse gas increases. Using qualitative and possibilistic tools, like the Ecological Discrete-Event Network (EDEN) framework, we integrated various variables (e.g., transportation, maritime activities, land artificialization, and blue carbon ecosystem development) into a decision-support model. We developed the Socio-Economic Net (SEN) model to evaluate whether the costal-urban La Rochelle Metropolitan Area (France) could achieve carbon neutrality by 2040 through adaptive management, while addressing 16 of the 17 Sustainable Development Goals (SDGs). Given prevailing social resistance to behavioral change, we hypothesized that this transition would be unattainable within the timeframe. However, our results demonstrated the opposite: carbon neutrality, alongside SDGs 13–17, was achievable under specific policy-driven scenarios. These included the implementation of green policies at national/EU levels, a shift from conventional to organic agriculture, and demographic stabilization. Critically, the SEN model revealed that top-down actions are essential to enable bottom-up changes, offering multiple, actionable pathways for local governments. For environmental managers and policymakers, this study demonstrates that systemic, multi-scale interventions can overcome apparent barriers to sustainability while also highlighting the trade-offs—economic, social, and ecological—that must be navigated. Finally, the EDEN framework offers a replicable approach for other coastal cities seeking to balance development and climate goals.

Keywords: social-ecological system; carbon neutrality; blue carbon; discrete-event modeling; qualitative modeling; coastal urban systems; Sustainable Development Goals (SDGs)

Glossary

EDEN: Ecological Discrete-Event Network (framework)

GHG: Greenhouse Gases

LRMA: La Rochelle Metropolitan Area

LRTZC: La Rochelle Zero Carbon Territory

SEN: Socio-Economic Net (model)

SESs: Social-ecological Systems

SDGs: Sustainable Development Goals

1. Introduction

Climate change mitigation has become a major scientific and policy priority over the past few decades, building on nearly two centuries of climate research (Budyko & Sedunov, 1990; Fourier, 1824; Plass, 1956; Sawyer, 1972). In 2015, the United Nations adopted the 2030 Agenda for Sustainable Development, establishing the 17 Sustainable Development Goals (SDGs) as a global framework for promoting environmental sustainability and human well-being (United Nations, 2015; see Supplementary Material 3). Although the Kyoto Protocol (1997) established the first legally binding greenhouse gas (GHG) emission reduction commitments, the Paris Agreement (2015) markedly accelerated international efforts toward carbon neutrality and net-zero emissions (Paris Agreement, 2015; UNFCCC, 1998).

Carbon neutrality aims to balance anthropogenic GHG emissions with carbon removal through natural and technological solutions (Ministère de La Transition Ecologique, 2020; Vasylyeva, 2021). Alongside terrestrial ecosystems, coastal vegetated ecosystems—including salt marshes, seagrass meadows, and mangroves—play a disproportionately large role in long-term carbon sequestration, a climate regulation service known as blue carbon (Duarte et al., 2013; Mcleod et al., 2011). Recognizing the mitigation potential of these ecosystems has broadened the scope of nature-based solutions to climate change. More than 130 countries have now adopted net-zero emission targets, including France, whose Stratégie Nationale Bas-Carbone (SNBC) provides the national roadmap for achieving carbon neutrality by 2050 by reducing their carbon footprint (Ministère de la Transition Écologique, 2020). However, ambitious climate targets alone are insufficient without effective implementation strategies and standardized approaches for assessing and reducing GHG emissions (Bruley et al., 2026; Halat et al., 2026). Identifying the principal drivers of emissions across different cities sectors is therefore essential for designing effective mitigation policies. In this context—and with 16 of the 17 SDGs in mind—the costal-urban La Rochelle Metropolitan Area (LRMA, France) launched the La Rochelle Zero Carbon Territory (LRTZC) initiative, which aims to achieve carbon neutrality by 2040. As a coastal territory, LRMA can also integrate blue carbon ecosystems into its broader climate mitigation strategy, highlighting the need for comprehensive assessments of both emission sources and natural carbon sinks.

Social-ecological systems (SESs), also known as city nexus, are complex and adaptable systems that help us understand and describe the connections and interactions between human societies and natural environments. They often exhibit great adaptive capacity due to their context-sensitive nature (Biggs et al., 2021; Holling, 2001; Levin, 2000). For example, Lansing & Kremer (1993) studied crop management systems on the island of Bali and observed the emergence of an extremely complex co-adaptation process, interlinking individual components such as cultural practices, farmers, crops, and physical geography. In this context, studying SESs can help identify the "driving forces" responsible for GHG increases (e.g., by coupling human population dynamics, atmospheric carbon dioxide concentration, and social aspects) (Pal & Ghosh, 2023). Coastal cities are particularly influenced by global alterations such as GHG emissions, which increases the importance of studying how carbon emissions, particularly those related to blue carbon, behave in these ecosystems. To generate meaningful and valid data for later interpretation that incorporates all SES properties, it is critical to understand the causal relationships between the patterns and processes responsible for systemic behavior—including both anthropogenic and non-anthropogenic drivers. For this, a valid method must be used (Capra, 2005; Österblom et al., 2013). Therefore, the

use of models for carbon emissions due to cities and anthropogenic growth has increased (Ingty, 2021; Pal & Ghosh, 2023; Soergel et al., 2024; Wheeler, 2017).

Quantitative modeling often requires detailed parameterization that is unavailable for both SESs and net-zero emission targets (Cole et al., 2025; Jakeman & Letcher, 2003; McCallum, 2008; Nikolić & Ewart, 2025; Wachsmuth et al., 2023). In contrast, qualitative and possibilistic – i.e., non-probabilistic and non-deterministic approaches— such as the Ecological Discrete-Event Network (EDEN) framework (Gaucherel, et al., 2024 a) — allow for the integration of highly diverse ecological and socio-economic variables (e.g., individual transportation, policy implementation, land use, food systems, and blue carbon area development). These approaches can capture potential trajectories of city nexus even under conditions of limited data availability, making them particularly valuable for exploring the dynamics and underlying drivers of SESs. Furthermore, the qualitative approach is well-suited for use by both scientists and stakeholders, increasing the uptake of model results and adding a more holistic interpretation to them (de Lapparent et al., 2025; Gourguet et al., 2021; Herzberg et al., 2026; Lehtiniemi & Paloniemi, 2023; Zheng et al., 2024). EDEN has already been validated for specific social-ecological systems and provided insightful understanding of possibilistic pathways and decision-making for achieving an integrated agritourism system (De Lapparent et al., 2025 b), for sustainable crop-livestock integration (Cosme et al., 2024), and for relating water resources to a highly touristic tropical island (Bois et al., 2025).

The objective of the Socio-Economic Net (SEN) model developed here was to evaluate whether contemporary society can modify its practices (e.g., types of agriculture, carbonated or non-carbonated individual transport, food consumption) to achieve carbon neutrality in the LRMA by 2040 as a socially resilient city. Given the apparent reluctance of society to substantially change its behavior, this study hypothesizes that such a transition may not be attainable within this limited timeframe (J. Andersson & Hellsmark, 2024; Qi et al., 2026; Zheng et al., 2024). The EDEN framework was employed to develop a clear and structured representation of the SES dynamics of the LRMA. This integrative model incorporates human dimensions (social, economic, and political) alongside environmental components (green and blue carbon areas) to address the research question. By focusing on the LRMA as a case study, investigating pathways to achieve zero carbon not only yields targeted policy and management recommendations but also offers scientific insights and a model that can be replicated in other similar regions worldwide (Mat et al., 2016).

2. Materials and Methods

2.1. Why La Rochelle Metropolitan Area and what is LRTZC?

This study was conducted at the scale of La Rochelle Metropolitan Area (LRMA), located along the French Atlantic Coast. This area is composed of a total of 28 towns and villages with 175 600 inhabitants, representing a total surface of 327 km^2. In the year 2019, the La Rochelle Zero Carbon Territory (LRTZC) project was found, with the objective of reducing carbon emission of the area as to achieve carbon neutrality by the year 2040 and was established in lined with the Intergovernmental Panel on Climate Change (IPCC) and United Nations SDGs objectives (La Rochelle Territoire Zéro Carbone, 2019; PCAET, 2024; United Nations, 2015). LRTZC has been conceived and is carried out by the hand of 5 stockholders: La Rochelle conurbation community, La Rochelle City center, La Rochelle University, La Rochelle Commercial Port and the Atlantech association. There are 130 partners

which support this project. As LRMA is delimited by 70 km of coastal line, LRTZC project can rely on reducing carbon emissions via the carbon stock capacity of its' littoral as a part of blue carbon areas. Nonetheless, an additional compensating effort from regional and national society must be accomplished.

LRTZC carbon reduction objectives are focused on the development of non-carbonated transportation, green energy consumption, industrial and housing energetic renewal, as in increasing carbon sink areas and their stock capacity (Table 1) (Afonso et al., 2025; PCAET, 2024). These main axes have been chosen after rigorous research between the scientific consortiums due to intensive surveys of LRMA emissions and literature background worldwide and are aligned with all the SDGs objectives, excepting Goal 5 which is not directly related (Paris Agreement, 2015; PCAET, 2024; Plans Climat, 2015; see Supp. Mat. 3).

Table 1 Carbon budget at La Rochelle Metropolitan Area (LRMA) in 2019 and the carbon budget objective for 2040 for the main variables chosen by the IPCC, (2014) and PCAET (2024) regulations and LRTZC consortium. Carbon budgets unite in tons CO_2 eq $year^{-1}$

Carbon budget in 2019		Carbon budget objective 2040	
PCEAT (2024)	LRTZC	PCAET (2024)	LRTZC
Inputs and consumption = **774 000**	Food = **397 356** Domestic products produced and consumed = **376 723**	Inputs and consumption = **194 000**	Food = **98 9400** Domestic products produced and consumed = **95 060**
Total transportation = **509 000**	Individual trips = **338 899** Merchandise = **169 748**	Total transportation = **127 000**	Individual trips = **84 583** Merchandise = **42 416**
Commercial activities = **299 000**	Industries =**112 248** Tracks (Artificialization) = **141 175** Agriculture and fishing = **45 189**	Commercial activities = **75 000**	Industries = **28 500** Tracks (Artificialization) = **35 250** Agriculture and fishing = **11 250**
Housing = **302 000**	Housing (Residential emissions) = **302 279**	Housing = **76 000**	Housing (Residential emissions) = **76 000**

2.2. Modeling the socio-economic system of LRMA with the EDEN framework

The Ecological Discrete-Event Network (EDEN) modeling framework (Gaucherel & Pommereau, 2019; Pommereau et al., 2022), which is based on a qualitative and discrete-event formalism, was used to create the Socioeconomic -Net (SEN) model. *Variables* in this model are Boolean and can only take two values: either "functionally present" ("+" or On) or "functionally absent" ("-" or Off), defined by a threshold. This threshold varies depending on the meaning of the variable, which could represent, for example, the gain or loss of waste tonnage, a higher or lower annual population movement or even a carbon footprint variation (Table 2, Fig. 1). After variables are chosen, an initial state is defined. To simulate an annual cycle, two initial states were defined for the SEN model: 1) *Summer at LRMA* and 2) *Winter at LRMA*, following literature on La Rochelle seasonal variability (Bilan des trafics de port, 2025; CdA de La Rochelled'Agglomération, 2024). Variables together build a *system state*. System states are computed by "*if-then*" rules (Fig. 1), which combine variables involved into

specific (i.e., social, ecological or economic) processes. Once a rule fulfills its *conditions*, it can be executed, following a *condition* >> *realization* change (Gaucherel, et al., 2024 a) (Fig. 1). As "*if-then*" rules are updated asynchronously, they apply independently and one at a time. Hence, alternative trajectories might be computed from any given state. Furthermore, none of these trajectories are chosen and all possible are computed, opening the widest range of the system dynamic. Therefore, this model is non-deterministic and non-probabilistic; the EDEN framework is thus defined as *possibilistic* (Gaucherel, et al., 2024). While most rules are non-mandatory (i.e., they represent a process that may happen), constraints represent faster and/or mandatory processes and thus have a higher priority. In the SEN model, 105 rules and 5 constraints have been defined (Table S1).



Fig. 1 Illustration of simplistic recycling system with (right) its associated rule-based model made of two variables (Pop, Was) and five rules, and (left) the resulting state space. Transient states are characterized by discs and deadlocks by a square. Edges illustrate transitions between states. Variables can be either systematically present (black) or absent (grey) in each state of the set

The computation of the system dynamics in EDEN models is called a State-Transition Graph (STG) or model dynamics, where system (here a specific moment in society) states and transitions (switch from one state to another) are represented by nodes and edges respectively. Three main topological structures that can be observed in the model dynamics are: structural (cycling) stabilities, transient state successions and stable (deadlock) states. Structural stabilities are characterized by a subset of mutually reachable states (Gaucherel & Pommereau, 2019), meaning that any change inside the structural stability is reversible. When structural stability cannot be left, it is called a "terminal stability" or a "deadlock" for an isolated state (and all isolated states leading to this final state). Transient states are a set of states which share common subsequent states (Gaucherel & Pommereau, 2019). Additional information about this method, its illustration and technical details are found in previous works (Cosme et al., 2024; Gaucherel, et al., 2024 b; Gaucherel & Pommereau, 2019). The model analysis was by the hand of Jupiter environment, a user-friendly platform that relies on Python 3.7.5.

2.3 Variables choices, which and why?

To support and increase LRTZC existing data (Afonso et al., 2025; PCAET, 2024) (Table 1), a total of 19 people were interviewed, with ten individual and five workshops (2 people or more) were carried out between March 2024 and February 2025 at LRMA. Interviews are useful for analyzing socialization processes (Carter & Montes Alvarado, 2019). Semi-structured interviews were used for collecting data during surveys (Patton, 2002).

Interviews were organized in two stages (Richard et al., 2022). The first stage was devoted to a description of the subject's trajectory and their relationship with the project, while the second stage examined in detail their relationship with LRTZC objectives, mainly with carbon emissions. The aim was to discuss the knowledge, implications, hopes and expectations on carbon neutrality at LRMA and the different points of view on the subject.

Interviewees were chosen according to their relationship (direct or indirect or no-relationship) to LRTZC project, including project coordinators and the scientific consortium, researchers, stakeholders as well as LRTZC PhD students of different disciplines. A qualitative methodology for the data collection analysis process was applied (Tracy, 2010). Each interview, either individual or group, lasted an average of two hours, followed by condensation and transcription for later analysis (Burnard, 1991). Participants' names were changed to preserve their confidentiality (Tracy, 2010). Transcriptions were read three times for better analysis, each of which had a different objective. The first reading helped understanding the content of the interviews, the second aimed to generate initial inductive codes (Hall et al., 2012) and the third and last reading was conducted for rearranging the corpus for data interpretation (Braun & Clarke, 2006). Variables selection was held once the transcript analyses were finished, by choosing the most recurrent elements in addition to LRTZC pre-chosen variables.

A total of 23 variables were carefully chosen and divided into four categories: social structure (1), resources and consumption (2), carbon emissions (3) and economic activities (4) (Table 2; Table 3). Eight variables were selected out of the LRTZC project objectives (Table 1). The remaining 15 variables were carefully defined with the interviews results and an intensive survey through literature to simulate any city in the world as accurately as possible (Table 2).

Table 2 Chosen variables for the Socioeconomic -Net (SEN) model for La Rochelle Metropolitan Area (LRMA). Variables are divided into four categories: social structure (1), resources and consumption (2), carbon emissions (3) and economic activities (4) (Table 3). Their value can be either above ("+") or below ("-") their chosen threshold. Bibliography and data of LRTZC program were used to choose the thresholds. Pictograms were used to characterize variables in the following figures.

N°	Acronym	Pictogram	Interpretation	Meaning +	Meaning -	Threshold	Reference
1	**Pop+**		Number of households at LRMA/ year	more than	less than	91 900 households	INSEE (2022)
	Inc+		Income per household at LRMA	higher than	less than	24 000 E/year (2000 E net/month)	INSEE (2022)
	Job+		Active workers at LRMA	more than	less than	75% (active + retired today) / 71 000 employees	INSEE (2022)
	Npo-		National/UE policies	Implementation	Lack of implementation	Implementation of green policies (and means to decrease CO_2 emissions) at a national level	Mazeaud (2021, 2024); Mazeaud & Rieu (2021)
	Lpo-		Local policies	Implementation	Lack of implementation	Implementation of green policies (and means to decrease CO_2 emissions) at a local level	Mazeaud (2021, 2024); Mazeaud & Rieu (2021)
	Fin+		Financial support	Sufficient	Insufficient	82 million € financial support for LRTZC	LRTZC program (2026)
	Will-		Political/Industrial will to support/implement green policies	Present	Absent	Create new programs and/or support existing ones	LRTZC consortium
2	**Foo+**		% of food produced and consumed that comes from the region	food from the region	food from outside the region	25% of local food consumption *	PAT (2021)
	Dpc+		Domestic products produced and consumed at LRMA	more consumption	less consumption	5% GDP consumption *	PCAET (2024)
	Was+		Tons of waste per year at LRMA	more	less	549 800 Tons of waste at LRMA	PCAET (2024)
	Rec-		Recycling capacity at LRMA	more recycling	less recycling	20% recycled products *	PCAET (2024)
3	**Hou+**		Residential emissions at LRMA	higher emissions	lower emissions	76 000 tons CO_2 eq $year^{-1}$ *	PCAET (2024)
	Tra+		Individual carbonated Transportation at LRMA	more	less	84 600 tons CO_2 eq $year^{-1}$ *	PCAET (2024)
	Cfp+		Carbon footprint of LRMA	higher FP	lower FP	472 000 tons CO_2 eq $year^{-1}$ *	CdA de La Rochelle (2019)
	Tye+		Type of energy used at LRMA	carbonated	non-carbonated	Carbonated	
	Bca-		Blue Carbon area	larger surface	smaller surface	40 300 ha	Dupuy et al. (2022); PCAET (2024)
	Gca-		Green Carbon area	larger surface	smaller surface	3 500 ha (non-constructed land)	PCAET (2024)
	Tri+		Carbon tons of leisure trips $year^{-1}$ at LRMA	More than	smaller number	47 000 tons CO_2 eq $year^{-1}$ of plain and cruise ship	Bilan des trafics de port (2025), PCAET (2024)
4	**Agri-**		AGRI BIO production at LRMA	BIO production	Non-BIO production	50 % of sustainable and adapted to the environment production *	PAT (2021)
	Port+		Maritim carbon emission at LRMA	higher	lower	21 000 tons CO_2 eq $year^{-1}$*	Bilan des trafics de port (2025)

Ind-		CO_2 eq production of industrial nature at LRMA	more than	less than	27 000 tons of CO_2 eq $year^{-1}$*	PCAET (2024)
Cons+		m² of artificialized surface at LRMA	higher	smaller	116600 t CO_2eq $year^{-1}$ * artificialized surface	CdA de La Rochelle (2019); PCAET (2024)
Tou+		Number of tourists per year at LRMA	more than	less than	225 000 tourists 2023	CdA de La Rochelle (2024)

205 * Threshold defined by LRTZC (PCAET, 2019)

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207 **Table 3** Variables' categories divided by number (N°), nature (either chosen by the La Rochelle Zero Carbon Territory (LRTZC) consortium or literature) and description for
208 La Rochelle Metropolitan Area (LRMA). Each variable is described and presents its acronym as mentioned in Table 2

N°	Categories	Nature	Description
1	**Social structure**	Literature	Number of households at LRMA per year (Pop); income per household at LRMA (Inc); active workers at LRMA (Job); National/European policies (Npo); Local policies (Lpo); Political/Industrial will to support/implement green policies (Will); Financial support (Fin)
2	**Resources and consumption**	LRTZC objective	% of food produced and consumed that comes from the region (Foo); domestic products produced and consumed at LRMA (Dpc)
		Literature	Tons of waste per year at LRMA (Was); recycling capacity of LRMA (Rec)
3	**Carbon emissions**	LRTZC objective	Individual carbonated transportation at LRMA (Tra); residential emissions at LRMA (Hou)
		Literature	Type of energy used at LRMA (Tye); carbon Footprint of LRMA (Cpf), Blue Carbon (Bca); Green Carbon (Gca); Carbon tons of leisure trips (plain and / or cruise ship) per year at LRMA (Tri)
4	**Economic activities**	LRTZC objective	Maritime merchandise (Port); CO_2eq production of industrial nature at LRMA (Ind); m² of artificialized surface at LRMA (Cons); and a sustainable and adapted to the environment agriculture production at LRMA (Agri)
		Literature	Number of tourists per year at LRMA (Tou)

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On the other hand, favorable National/European or Local policies ("Npo" or "Lpo", respectively, Table 2) refers to the following laws and legislations:

- *At a National/European level*: Common Agricultural Policy (PAC, 2026) , climate and resilience plan (LOI N° 2021-1104, 2021), Zero Net Artificialization (Décret N° 2023-1096, 2023);
- *At a Local level*: Territory Nourishing Project (PAT, 2021), mobility orientation law (LOI N° 2019-1428, 2019). It also involves projects such as "Cooperative Carbone", that promote carbon emission mitigation through carbon credits.

Additionally, a few assumptions were made to make this model possible: when a National/European policy is implemented, local policies would follow the lead, meaning that it would not take longer than a few years (less than five) to establish (Mazeaud, pers. comm.). As this model is based on La Rochelle, some specific variables were chosen, i.e., Tou, as this city has a great influence on tourist activity and Bca, because 45% of LRMA land and sea surface (about 25.580 ha) is considered blue carbon areas (Afonso et al., 2025). Likewise, the long-term carbon storage capacity of wetland and coastal ecosystems depends on the preservation of these habitats and their good ecological condition (PCAET, 2024). Therefore, it is extremely important to consider them as variables.

Processes in the model are expressed on an annual timescale. So, while process may act at different scales (from seasonal to 15-yr long), CO_2 emissions are expressed on an annual timescale (at least).

2.4. Further analysis and validation

To validate the SEN model, the socio-economic transitions and trajectories using a temporal logic approach were analyzed. This method describes how system properties evolve over time in models driven by discrete events (Cordier et al., 2014; Cosme et al., 2024). Computation Tree Logic (CTL) (Clarke et al., 2018), tests whether a given property holds in at least one, or in all, possible future pathways starting from an initial state (Thomas et al., 2022). This approach makes it possible to verify whether any system states appear in the State Transition Graph (STG). For example, CTL can be used to determine whether carbon capture can never, may, or must evolve into a carbon emission (Cosme et al., 2024). The CTL queries were defined based on existing knowledge of LRMA socio-economic evolution and LRTZC queries (Table 2, Table 4). In addition, a comparison between LRMA past socio-economic system was held to verify SEN's correct function (Table 4).

Temporal relationships were represented using the operators **E** (Exist) and **F** (Finally), while the Boolean operators **AND** (∧), **OR** (∨), and **NOT** (¬) were included in the evaluated formulae. The extensional operator **∃** was also applied to express specific conditions. The combination of these operators allows the formulation of complex dynamical properties (see Cosme et al., 2024; Thomas et al., 2022). To ensure the correct dynamic of the models' transitions, *trap* set of states must be searched. If a set of states is *trapped*, there is no guarantee of an exit existence and so, if they are interpretated as any other set of state with a "free exit", the analysis of the models' dynamics would be misleading (Pommereau, 2025).

The presence of three "wanted properties" and two "unwanted properties", as well as their connections and dynamics were studied using CTL formulae on a model dynamics with an automated *model-checker* tool (Thierry-Mieg, 2015; Thomas et al., 2022). Thus, the presence of every state, their associated transitions and complete trajectories in the model were automatically checked. The three "wanted properties" were defined, of increasing complexity, and looked for in the integrated model (Table 5; see Supp. Matt. 3 for SDGs identification):

- *Net* only focused on the low carbon food print objective and SDG 13;
- *LRTZC* contained the most crucial axes for reducing emissions as well as SDG 7, 12, 13, 14, 15 and 16;
- *LRTZC+* that expressed an ideal state, were not only LRTZC main variables were found, but it also counts with an increase on active people (Job), recycling percentage (Rec) and tourism (Tou) and a decrease on the amount of waste (Was) and carbonated leisure trips (Tri). This addition included SDG 2, 8, 12, 13, 14, 15, 16 and 17.

Two "unwanted properties", *Degraded* and *Distorted Future*, were defined as antagonist properties, meaning that neither of LRTZC objectives nor carbon neutrality would ever be achieved (Table 5). In addition, the main rules governing socio-economic emissions and carbon behavior were analyzed to assess the potential effects and underlying causes of these transitions. Together, these analyses evaluate the model's ability to reproduce observed socio-economic dynamics and identify the key factors driving their influence on carbon dynamics.

Table 4 La Rochelle Metropolitan Area socio-economic behavior between 1900 and 2026. For variables descriptions see Table2. Variables can be either functionally present ("+"), absent ("-") or non-defined ("*").

Variables/ Years	Pop	Inc	Job	Tou	Npo	Lpo	Fin	Will	Foo	Dpc	Was	Rec	Hou	Tra	Cfp	Tye	Tri	Agri	Port	Ind	Cons	Gca	Bca
Today (2026) (Initial state)	+	+	+	+/-	-	-	+	-	-	+	+	-	+	+	+	+	+/-	-	+	+	+	-	-
2000[1,3,4,6]	+	+	+	+	-	-	*	*	-	+	+	-	+	+	+	+	+	-	+	+	+	-	-
1950[1,2,3,4,5,6]	+	*	*	+	*	*	*	*	*	*	*	*	*	*	*	+	*	*	+	+	*	*	*
1900[1,3,4]	-	*	*	-	*	*	*	*	*	*	*	*	*	*	*	*	*	*	-	*	*	+	+

References: [1]Gerber & Nibodeau, (2014); [2]Manceau (2025); [3]Marnot (2021); [4]Woessner (2021); [5]Jean (2025), [6]Rey (1977)

Table 5 Definition of wanted and unwanted properties. For variables descriptions see Table 2. Variables can be either functionally present ("+"), absent ("-") or non-defined ("*"). Variables change in the initial state, depending on seasons (Summer: "+", Winter: "-").

Variables/ Properties	Pop	Inc	Job	Tou	Npo	Lpo	Fin	Will	Foo	Dpc	Was	Rec	Hou	Tra	Cfp	Tye	Tri	Agri	Port	Ind	Cons	Gca	Bca	SDG
Today (Initial state)	+	+	+	+/-	-	-	+	-	-	+	+	-	+	+	+	+	+/-	-	+	+	+	-	-	-
Net	*	*	*	*	*	*	*	*	*	*	*	*	*	*	-	*	*	*	*	*	*	*	*	13[1]
LRTZC	*	*	*	*	*	+	+	+	+	-	*	*	-	-	-	-	*	+	-	-	-	*	*	7, 14, 15, 16, 17[1]
LRTZC+	*	*	+	+	*	*	+	+	+	-	-	+	-	-	-	-	*	+	-	-	-	+	+	2, 8, 12[1]
Degraded	*	*	*	*	*	*	*	*	*	*	*	*	+	+	+	+	+	*	+	*	*	-	-	-
Distorted Future	+	-	-	-	-	-	*	*	-	+	+	-	+	+	+	+	+	-	+	+	+	-	-	-

[1] SDG from Net is also included in LRTZC and LRTZC+, and those from LRTZC are included in LRTZC+

3. Results

3.1. The Socio-economic system dynamics

LRMA past socio-economic system (Table 4) were retrieved and reached within the SEN computed dynamics (Fig. S1). More precisely, all observed states were reversely connected (*1950, 2000* and *Today(2026)*), excepting 1900 who contained the final state (deadlock). So, as a first and central result, the SEN model was validated.

A total of 28 035 states were reachable. The interaction (processes) network provided the summarized dynamics of the integrated SEN model (Fig. 2). Variables spatially close are those who interact the most within each other in this socio-economic skeleton, while peripheral variables will rely mostly on them. Amongst the 23 defined variables (Table 2), six stood as central, driving the model's dynamic: Political/Industrial will to support/implement green policies, a sustainable and adapted to the environment agriculture production at LRMA, number of tourists per year at LRMA, individual carbonated transportation at LRMA, National/European policies and carbon Footprint of LRMA (Fig. 2). Seven variables were standing between central and peripheral ones: CO_2eq production of industrial nature at LRMA, type of energy used at LRMA, tons of waste per year at LRMA and residential emissions at LRMA, % of food produced and consumed that comes from the region, financial support and local policies (Fig. 2). Even though the left variables were peripheral and their effect would seem to have a lower impact on the system functioning, they were also crucial when understanding carbon dynamics.

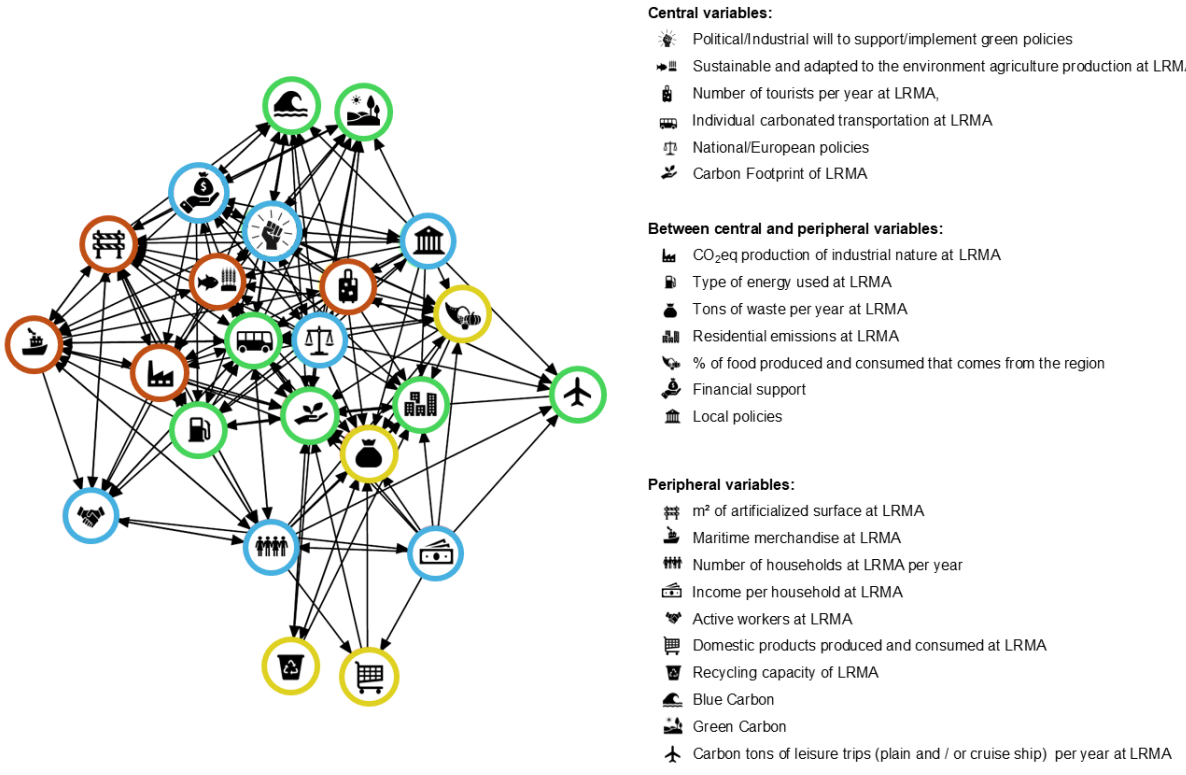


Fig. 2 The Interaction network of the integrated socio-economic net (SEN) model. The graph nodes contain the 23 variables; either central, peripherical or in between them. Interactions (graph edges) are connected from conditions to realizations, oriented from the edge foot to the edge head, with at least one rule connecting them. Variables are divided into four categories: social structure (blue), resources and consumption (yellow), carbon emissions (green) and economic activities (red)

3.2. Finding Carbon Neutrality

The SEN model dynamics analysis presented a total of 27 sets of states, here after called *regimes* (Fig. 3). From these regimes, 20 were unexpected states (D1 to D6; NN1 to NN3; De1 to De4; N1 to N3; L1 to L3 and the deadlock) while the other seven were the expected ones (both initial states (ISW and ISS); *Dangerous* (D); *Distorted Future* (DF); *Net* (N); *LRTZC* (L); *LRTZC*+ (L+); Table 5) (Fig. 3).

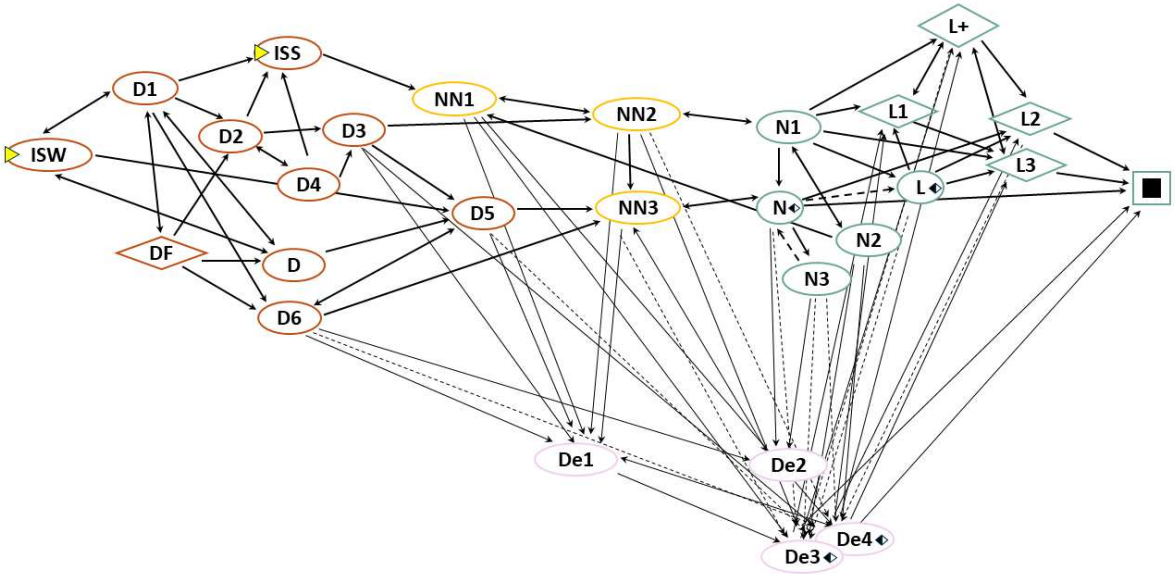


Fig. 3 Simplified model dynamics of the Socio-economic Net (SEN) model. The yellow triangle represents the initial states (Summer: ISS, Winter; ISW); the black square represents the final state (deadlock) and the black and white diamond a trapped set of states. Transient states are characterized by discs, structural stabilities by circles and deadlocks by a square. The desired properties are green (N, N1, N2, N3, L, L1, L2, L3, L+) and the undesired in red (D, D1, D2, D3, D4, D5, D6, DF) (Table 5); and unexpected states are in yellow (NN1, NN2, NN3) or pink (De1, De2, De3, De4). Long black arrows represent normal transitions, while dashed lines connected with *trapped* states. (see Fig. S2 for the whole model dynamics). Thicker lines denotate the main pathways while thine ones the misleading paths

A clear transition can be observed when looking at the model's dynamic graph, with four clear zones (Fig. 3, Fig S2). The first one was composed of a mix of 10 unwanted/unexpected states, including the initial states, seven different regimes of *Degraded* states and the *Distorted Future* (DF) (Fig. 3). All these states presented the combination of variables described as a *Dangerous* state (Table 5), adding for each a different characteristic making them unique (i.e., D1 had a constant presence of luxury trips added to the Dangerous pre-definition (Fig. 4)). The second group was composed of only the *No-Net* regimes (N1 to N3), and which were never able to achieve carbon neutrality, as the carbon footprint variable was always above the threshold ("Cfp+"). Nonetheless, these regimes presented SDG 16. Following them were the wanted states, combining the *Net*, *LRTZC*, *LRTZC*+, deadlock and six unexpected regimes (three Net (N1 to N3) and three LRTZC (L1 to L3)) (Fig. 3). Once again, each unexpected state, including the deadlock, presented a combination of the expected variables from *Net* and

LRTZC with a small addition (i.e., N1 had a constate presence of tourists and National policies implementation; while L3 had LRTZC objectives and a high number of active workers and recycling effort (Fig. 4)). Interestingly, bot *Net* and *LRTZC* rested as trapped states, but a few transitions existed as possibilities for entering and leaving those states. Lastly, four *Deceptive* regimes were obtained, presenting systematically at least one trapped state inside them, reason why they could become a "threat" (Fig. S2, Fig. 3. For more information see Data Repository; Zenodo (2026)).

3.3. Following the road to *LRTZC*

Two main pathways were found for achieving both carbon neutrality (*Net*) and LRTZC objectives' (*LRTZC*) from any initial state (Fig. 4; Fig. 5). The first and main one transited five regimes before arriving at *LRTZC*. Starting at *Winter* at LRMA (ISW), it had to pass through a *Degraded* state were luxury trips are always present (D1) to become a *Summer* at LRMA regime (ISS), followed by two *No-Net* regimes, in which National/European polities appear (SDG 16) as present and tourism remains above its threshold for a later arrive to a *Net* (N) regime where both of those variables are present (adding SDG 13) for finally arriving at *LRTZC* (including SDG 14, 15 and 17) (Fig. 4; Table 6). Once the LRTZC objective was accomplished, four paths can be taken before arriving at the deadlock. Three of them crossed through variant of LRTZC regimes (*Wealthy LRTZC* (L1): presented both recycling effort and income per household above their threshold *Travelling LRTZC* (L2): presented both recycling effort and tourists above their threshold and *Working LRTZC* (L3): presented both recycling effort and active workers above their threshold), while the fourth one passed by *LRTZC+* (Fig. 4). At the end, every regime finished at the deadlock, who was found to be another variation of *LRTZC* with the addition of SDG 2. When taking this pathway, it is important to keep in mind that there was a misleading path between N1, N and LRTZC, because both N and *LRTZC* regimes were found to be *trapped* and no untrapped transition was found these last two states (Fig. 4, steps 6b and 7).

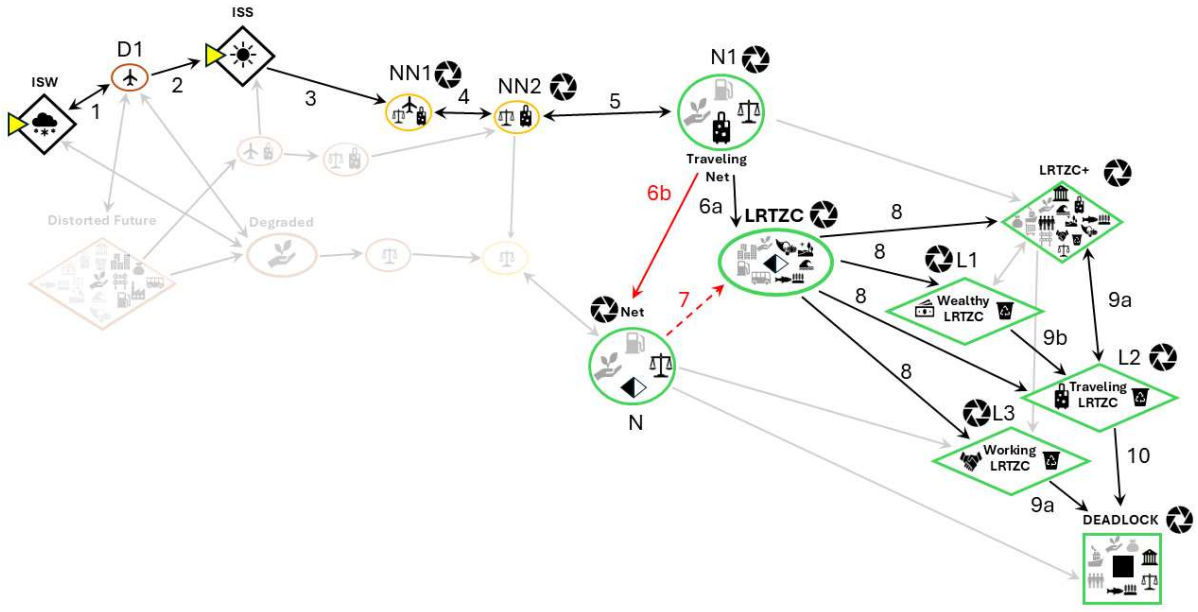


Fig. 4 Simplified view of the SEN models' pathways from any initial state to *LRTZC* property, passing by desired properties (green), undesired (red) and unexpected (yellow) ones, arriving at the deadlock (Table 5; Fig 3). The yellow triangle represents the initial state; the black square represents the final state (deadlock) and the black and

white diamond the trapped set of state (*trapped*). Black discs indicate that at least one SDG is achieved. Transient states are characterized by discs, structural stabilities by circles and deadlocks by a square. Black variables are constantly present, and gray ones are constantly absent (for threshold description see Table 2). Processes connecting each property are shown in Table 6 (steps 1 to 10). Black arrows show the selected pathways, the grey arrows represent alternatives, the red the misleading ones and the dashed red arrows the *trapped* connections

An alternative pathway was found for achieving carbon neutrality with only four steps (Fig. 5). Once again, two *Dangerous* (D, D5) and one *No-Net* (NN3) regimes needed to be crossed, where SDG 16 appears, before becoming a *Net* regime (Fig. 5; Table 7). Thus, this alternative transition showed that the only change that needed to be made to becoming a *Net* regime was to start implementing National/European policies (C1) (Table 7). However, LRTZC regime was not directly attained by using this pathway, but an alternative one was (*Working LRTZC* (L3)), with a latter arrived at the deadlock (Fig. 5).

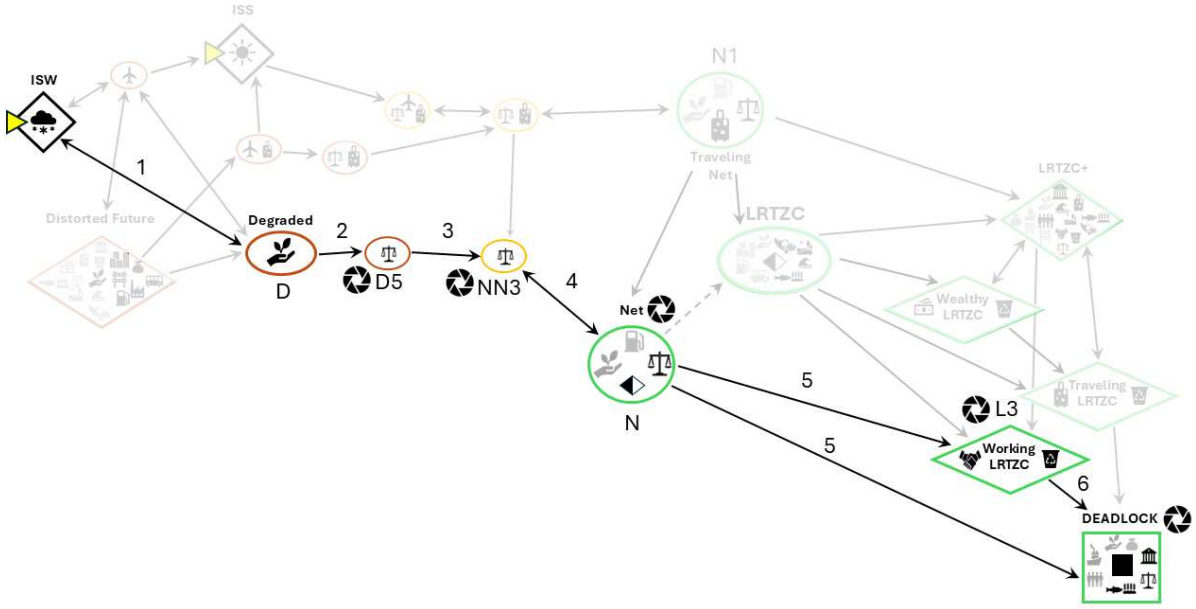


Fig. 5 Simplified view of the SEN models' alternative pathways from achieving carbon neutrality, passing by desired (green) properties, undesired (red) and unexpected (yellow) ones, arriving at the deadlock (Table 5; Fig 3). The yellow triangle represents the initial state; the black square represents the final state (deadlock) and the black and white diamond the trapped set of state (*trapped*). Black discs indicate that at least one SDG is achieved. Transient states are characterized by discs, structural stabilities by circles and deadlocks by a square. Black variables are constantly present, and gray ones are constantly absent (for threshold description see Table 2). Processes connecting each property are shown in Table 7 (steps 1 to 10). Black arrows show the selected pathways, the grey arrows represent alternatives

Table 6 Interpretation of rules responsible for transitions (pathway) from initial states (Summer and Winter) step by step at La Rochelle Metropolitan Area (LRMA). Processes (rules) connect each set of state (From – To). Steps 1 to 10 show the most direct trajectory from the initial states to *LRTZC* and *deadlock*. As rules are not mandatory, the verb "CAN" appears in every sentence, to highlight that the realization of the rules is only a possibility

Step	From	To	Rule	Interpretation
1	ISW	D1	R56	Wheatly people CAN consume more domestic products and luxury trips, generate more waste and generate more housing emissions
			R75	If households' income, domestic product consumption, individual and luxury trips are above their threshold, carbon foodprint CAN increase
2	D1	ISS	R90	If the number of shipments at the port is above its threshold, more tourist CAN by carbonated transport
3	ISS	NN1	C1	If financial support and willingness are above their threshold, National policies CAN be implemented
4	NN1	NN2	R14	If number of households at LRMA is under its threshold, individual transport CAN go under its threshold
			R55	Lower income CAN lead to lower carbonated transport
5	NN2	N1	R67	If domestic product consumption, carbonated individual transport, housing emissions, industries, construction, maritime activities are under their threshold and local agri-food is above its threshold, carbon foodprint CAN decrease
			R68	If domestic product consumption, carbonated individual transport, housing emissions, industries, construction, maritime activities are under their threshold and non-carbonated energy is used, carbon foodprint CAN decrease
			R69	If domestic product consumption, carbonated individual transport, housing emissions, industries, construction, luxury trips and tons of garbage are under their threshold, carbon foodprint CAN decrease
			R71	If domestic product consumption, carbonated individual transport, housing emissions are under their threshold and non-carbonated energy is used, carbon foodprint CAN decrease
			R74	If households' income, domestic product consumption, individual and luxury trips are under their threshold, carbon foodprint CAN decrease
6a	N1	LRTZC	R48	If the number of tourists is above its threshold and eco-tourism is engaged, blue and green carbon areas CAN increase
			R105	If there is less artificialization, blue and green carbon areas CAN decrease
6b	N1	N	R57	If the number of luxury trips per year decreases, less tourists CAN come to LR
7	N	LRTZC	R105	If there is less artificialization, blue and green carbon areas CAN decrease

8	LRTZC	L1, L2, L3, LRTZC+	R54	If there are favorable recycling politics, recycling CAN surpass its threshold
9a	LRTZC+, L3	Deadlock	R57	If the number of luxury trips per year decreases, less tourists CAN come to LR
9b	L1	L2	R59	Lower number of active people CAN decrease the income per household
10	L2	Deadlock	R14	If number of people et LR is under its threshold, individual transport CAN go under its threshold
			R45	If the number of tourists at LR are under their threshold, the number of active workers CAN also decrease
			R97	A change in politics CAN lead to lower emissions in constructions
			R98	If industries, individual transport and construction decrease, active workers CAN decreases

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366 **Table 7** Interpretation of rules responsible for transitions (pathway) from initial states (Summer and Winter) step by step at La Rochelle Metropolitan Area (LRMA). Processes
367 (rules) connect each set of state (From – To). Steps 1 to 6 show the most direct trajectory from the initial states to *LRTZC* and *deadlock*. As rules are not mandatory, the verb
368 "CAN" appears in every sentence, to highlight that the realization of the rules is only a possibility

Step	From	To	Rule	Interpretation
1	ISW	D	R45	If the number of tourists at LR are under their threshold, the number of active workers CAN also decrease
2	D	D5	C1	If financial support and willingness are above their threshold, National policies CAN be implemented
3	D5	NN3	R17	If there are policies that help people finance non-fossil fuels, the type of energy CAN change
			R19	If more "green" policies are in use, non-carbonated energy CAN be used and house emissions reduced
			R23	If more "green" policies are in use, industries CAN start using more non-carbonated energy
			R88	If import of carbonated fuel decrease, so CAN CO_2 emissions related to the port.
			R103	A change in politics CAN lead to lower emissions in constructions
4	NN3	N	R67	If domestic product consumption, carbonated individual transport, housing emissions, industries, construction, maritime activities are under their threshold and local agri-food is above its threshold, carbon foodprint CAN decrease
			R68	If domestic product consumption, carbonated individual transport, housing emissions, industries, construction, maritime activities are under their threshold and non-carbonated energy is used, carbon foodprint CAN decrease
			R69	If domestic product consumption, carbonated individual transport, housing emissions, industries, construction, luxury trips and tons of garbage are under their threshold, carbon foodprint CAN decrease
			R71	If domestic product consumption, carbonated individual transport, housing emissions are under their threshold and non-carbonated energy is used, carbon foodprint CAN decrease
			R74	If households' income, domestic product consumption, individual and luxury trips are under their threshold, carbon foodprint CAN decrease
5	N	L3, Deadlock	R105	If there is less artificialization, blue and green carbon areas CAN decrease
6	L3	Deadlock	R57	If the number of luxury trips per year decreases, less tourists CAN come to LR

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On the other hand, when running a SEN model where National Policies are not implied (Fig S4; Table S1, rule C1), even when willingness and financial support were above their threshold, none of the wanted states were found; though, every unwanted state was found (Fig. 6). In this "broken" version of the model, where carbon neutrality was never found, six main regimes were found, the *Initial Winter State* (ISW), the *Distorted Future*, the *Degraded* regime, and two unexpected versions of the *Initial Summer State* (D – ISS and D – Will) (Fig. 6). In addition, another deadlock was found, but this time it was a version of a *Degraded* state (Fig. 6). This new deadlock did not have enough green or blue carbon areas, nor local food consumption or recycling effort. In addition, Local policies were always under its threshold, so no help from the region could be provided (Fig. 6). In this broken version of the model the only structural stability present was the Degraded state and the deadlock, showing that the model would only remain at a certain time before arriving at the final state. Here, as Goal 16 is excluded, none of the other goals were achieved (see Supp. Mat. 3).

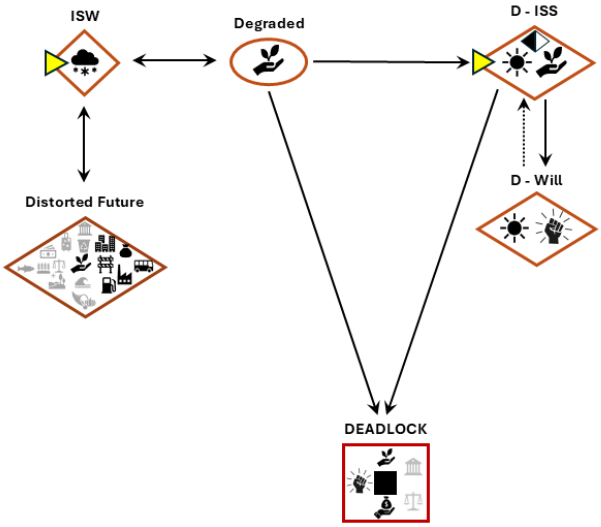


Fig. 6 Simplified view of the SEN models dynamic with National/European policies variable under its threshold. Both expected and unexpected state were undesired (red) (Table 5). (ISW: *Initial Winter State*; Degraded: equals *Degraded*; Distorted Future: equals *Distorted Future*; D-ISS: isin *Degraded* and *Initial Summer State*; D-Will: isin *Degraded* and has *Will+* and *Initial Summer State*; Deadlock equals *deadlock*). The yellow triangle represents the initial state; the black square represents the final state (deadlock) and the black and white diamond the trapped set of state (*trapped*). Transient states are characterized by discs, structural stabilities by circles and deadlocks by a square. Black variables are constantly present, and gray ones are constantly absent (for threshold description see Table 2). Long black dashes represent normal transitions, while dashed lines connected with *trapped* states. (see Fig. S4 for the whole model dynamics)

4. Discussion

Implementing concrete climate change actions requires an understanding of their underlying causes and plausible future scenarios. Many cities are relying on becoming more resilient by improving their waste management methods and recycling to boost their economies while reducing carbon emissions. For example, Finnveden et al. (2007) demonstrated that a robust and flexible integrated waste management system in Sweden can deliver both

environmental and economic benefits simultaneously. Meanwhile, China relies on "new technologies" to achieve carbon neutrality (Herzberg et al., 2026). In contrast, Chang (2013) argued that resolving the carbon emission problem requires economic redistribution between wealthy and poorer countries. Additionally, Pal & Ghosh (2023) emphasized that increasing forest cover and strengthening conservation policies are critical for reducing atmospheric CO_2 concentrations for reaching more resilient environments. In cities like the costal-urban La Rochelle, France, wetlands have been identified as key carbon sequestration areas—the so-called "blue carbon" (Amann et al., 2024; Mayen et al., 2023; Xaus et al., 2025). However, no country nor city has yet identified an ideal pathway to achieve this objective, as it requires untangling the complex, interconnected drivers at play. In this context, the EDEN model has enabled us to describe various pathways that could lead to the establishment of a carbon-neutral coastal city aligned with multiple Sustainable Development Goals (SDGs).

4.1. Carbon neutrality successes

Contrary to our initial hypothesis, carbon neutrality—and alignment with several SDGs—was achieved in the Social-Economic Net (SEN) model for the La Rochelle Metropolitan Area (LRMA). However, this result should be interpreted considering the specific local circumstances and social environment. As Vandenbergh & Steinemann (2007) noted, one of the greatest challenges in climate action are the social aspects, mainly the difficulty to change individual behavior, given the widespread reluctance to abandon electricity, cars, and other high-emission commodities.

First, in 2018, LRMA received financial support for the La Rochelle Zero Carbon Territory (LRTZC) project, which aimed to advance strategies for reducing carbon emissions while aligning with national policies that promote local research and industrial innovation, to become both a socially and environmentally resilient city. Under the coordination of the coastal-urban La Rochelle City Hall, a comprehensive stakeholder network was established, fostering institutional collaboration and strengthening the project's governance framework. Collectively, these efforts demonstrate a high degree of alignment with SDG 16 (Peace, Justice, and Strong Institutions) and SDG 17 (Partnerships for the Goals), by promoting effective institutional cooperation and multi-stakeholder partnerships. Furthermore, researchers from diverse disciplines—including biology, sociology, and political science—developed a robust knowledge base to identify and understand the key factors influencing blue carbon emissions (Amann et al., 2024; Dupuy et al., 2022; Mayen et al., 2023; Mazeaud, 2024; Mazeaud & Rieu, 2021; Pignon-Mussaud et al., 2025; Xaus et al., 2025). This interdisciplinary research further supports the achievement of SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land) by providing scientific evidence to inform sustainable policies and management practices.

An intriguing finding was that all initial states in the model were classified as "Dangerous". Not only is this alarming, but achieving carbon neutrality (Net regime) requires transitioning through a few "Degraded" and "No-Net" regimes (Fig. 4 and 5). This result aligns with Zhan et al. (2024), who projected that carbon emissions in the Beijing-Tianjin-Hebei region, China, would peak around 2060 before rapidly declining toward carbon neutrality. Similarly, Ding et al. (2010) observed that both developed and developing countries (e.g., Brazil, Canada, the UK) followed comparable pathways. In both cases, the persistence of carbon emissions despite mitigation efforts could be attributed to a lagging effect.

Notably, the SEN model not only identified all desired states but also revealed a final "deadlock" state with LRTZC characteristics (Fig. 4), including a reduction in the carbon footprint of housing, individual transportation, maritime and industrial emissions, and domestically produced/consumed goods, while increasing blue (and green) carbon areas, among others. This suggests that LRMA could remain permanently carbon neutral. However, a closer analysis of the deadlock regime raises concerns. For instance, the model requires a reduction in the number of households in LRMA, as a decrease in population - the growth in their levels of consumption - will enable a decrease in housing emissions, domestic product consumption and tons of waste (Jones & Kammen, 2014, 2014; Satterthwaite, 2009, 2011). Additionally, when running the "broken" SEN model (i.e., without National/European policies), the deadlock shifts drastically to a "Degraded" LRTZC regime (Fig. 6). This indicates that financial support and local eco-friendly measures alone are insufficient for achieving carbon neutrality; rather, national (or even continental, in the case of the EU) alignment is essential (Vandenbergh & Steinemann, 2007). For example, a French mayor removed dykes from the coastline to allow the ocean to follow its natural course while increasing blue carbon areas (Boucard et al., 2016; PNR, 2022). Research from the LRTZC program saw that blue carbon areas at LRMA such as saltmarshes have a strong sequestration rate (–483 g C m^{-2} y^{-1}; Mayen et al., 2024 and -345 g C m^{-2} y^{-1}; Amann et al., 2023, 2024).

Another eco-friendly measure may be improved by environmental performance through green innovations such as digital technologies or climate-smart infrastructure (Gigauri et al., 2024; Mo et al., 2023; Trofymenko et al., 2023). Another example is the HOHO Wien building in Austria, which demonstrates how sustainable structural systems can enhance energy efficiency and reduce the carbon footprint of building materials (Baboun Nassar, 2024; Yanılmaz, 2023). Alternatively, Hu et al. (2026) found that a focus for decreasing GHG should be on heating and cooling efficiency of buildings.

4.2. The price to pay

Our analysis revealed that carbon neutrality in the LRMA was primarily achievable due to the implementation of National/European decision support strategies, including the use of carbon credits, increased local food consumption and a shift in agricultural funding (from non-organic to organic). Without these policies, the model showed that only undesired outcomes would emerge (see Data Repository; Zenodo link, 2026). Furthermore, both the "Net" and "LRTZC" regimes—and their unexpected variations (N1–N3 and L1–L3)—as well as "LRTZC+" only appeared when the use of carbonated energies decreased (SDG 7: Affordable and Clean Energy) (Fig. 4 and 5). Moreover, the computed system deadlock was only achieved under four conditions:

- Increased organic agriculture, local food consumption, and recycling efforts in LRMA (Coelho et al., 2018; Mo et al., 2023);
- A developed recycling effort (Turner et al., 2015);
- A reduction in the number of households and tourists in LRMA (Brown, 2015; Song et al., 2015);
- A decrease in luxury trips (like airplanes or cruise ships) (Meunier & Grillet, 2025);

One potential pathway for becoming a socially and environmentally resilient city could involve local policies requiring institutions such as schools, hospitals, and retirement homes to consume local and organic food. This would boost LRMA's economy through local profits while promoting eco-friendly economic activities. Additionally, national laws should prioritize financial support for sustainable agriculture over large-scale industrial

farming, to maximize impact (Hérault, 2022; Ledroit, 2026; Légifrance, 2026). Likewise, addressing negative dietary patterns should become a policy priority, given their growing health impacts (Gasparatos, 2026). As Mo et al. (2023) and Okolo et al. (2026) suggested, financing "green" (organic) agriculture can reduce agricultural carbon emissions (increasing "green carbon" capacity) while enhancing agricultural industrial structures and technology. Overall, food transitions can benefit both the economy and human/environmental health (Gasparatos, 2026) and lead to the emergence of SDG 2 (Zero Hunger). These changes could also impact blue carbon areas through water runoff, which may carry nutrients, pesticides, and other pollutants, affecting living organisms and the chemical composition of the environment (Grant & Payne, 1982). Similarly, Mason et al. (2003) found that herbicide use in English saltmarshes could reduce sediment stability, decrease photosynthesis in plants and phytoplankton, and impair carbon assimilation.

Another option could be to adopt recycling as an economic tool, as Nordic countries (C. Andersson & Stage, 2018; Finnveden et al., 2007) and Canada (Ferrara & Missios, 2005) have done. Increasing recycling efforts could not only serve as an economic driver toward resiliency but has also proven valuable for reducing carbon emissions (Turner et al., 2015). As Ma et al. (2024) proposed, to decrease carbon emissions while maintaining economic growth, urban agglomerations and cities should align their economic characteristics and develop them sustainably, promoting mutual benefits. For tourist-dependent cities like coastal-urban La Rochelle, eco-tourism could be reinforced through initiatives such as visits to different types of marshes, promoting local restaurants (with oysters, a regional specialty) and/or organizing bicycle rides around the city and its surroundings. Expósito & Berbegal-Zaragoza (2026) found that a significant proportion of tourists would be willing to pay a "visitor's fee" to prevent coastal degradation. Another approach could be to increase train travel and reduce air travel by reallocating financial support from airlines to railways (Meunier & Grillet, 2025). Alternatively, carbon stock capacity in blue carbon areas could be enhanced by integrating nature-based solutions into wetland and coastline management (Borbhuyan et al., 2026).

4.3. EDEN as a useful tool

Once again, the EDEN Framework has demonstrated its effectiveness for analyzing complex socio-ecological systems, here within the context of zero-carbon and blue carbon research, incorporating sustainable, resilient and eco-friendly perspectives for cities and urban regions. However, this methodology should be used with caution. As a possibilistic and qualitative approach, EDEN lacks probabilistic and temporal dimensions in its rules and transitions, limiting the ability to derive time-bound conclusions. Nevertheless, in the absence of quantitative data, the possibilistic paradigm provides a robust framework for inferring system-level knowledge, including the sequencing of processes and the delineation of possible and impossible scenarios within a given context (Gaucherel, et al., 2024 a; Pommereau et al., 2022). The EDEN framework also demonstrates intuitive co-construction and strong integrative capacity, enabling the combination of highly heterogeneous components (variables) (Cosme et al., 2024; Gaucherel, et al., 2024 a), a reason why it may become another decision support tool in the near future. The SEN model was not only successful as an integrated SES model but also generated multiple pathways for achieving carbon neutrality—as well as highlighting misleading or discouraging ones.

Conclusion

The SEN model not only identified a possible pathway to carbon neutrality in the LRMA coastal city but also predicted that the region could remain a "neutral zone" indefinitely (deadlock) and that SDGs 2 and 13–17 could be achieved. However, such an outcome requires radical changes in National/European policies. Nonetheless, this model provided multiple possible pathways for achieving the research objective and demonstrated that, if certain top-down actions are implemented, zero carbon may be attainable, and the UN SDGs could be accomplished.

Statements and Declarations

Competing interests: The author has no competing interests to declare that are relevant to the content of this article.

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Data availability: Zenodo link: SEN Model for Jupyter (2026). Zenodo. https://doi.org/10.5281/zenodo.19631068 Additional data will be made available on request.

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