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Promoting the energy transition by leveraging bounded rationality and appropriately redesigned policies (PROBOUND)

PROBOUND Final report

including Deliverables

Bounded rationality in the Swiss mobility system

Recommendation for policy designs under consideration of BR

Redesigning policies in a bounded rationality framework

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Zusammenfassung

Das PROBOUND-Projekt zielt darauf ab, die Effekte der begrenzten (bounded) Rationalität (BR) der Akteure im Mobilitätssektor zu verstehen. Im Projekt werden eine Reihe von politischen Massnahmen (und ihre verschiedenen Ausgestaltungen) untersucht, die die BR der Verbraucher bei der Entscheidungsfindung im Bereich der persönlichen Mobilität in der Schweiz berücksichtigt und nutzt. Anschliessend werden die Auswirkungen dieser Massnahmen auf das Schweizer Net-zero Energiesystem quantifiziert.

Anhand einer Literaturübersicht haben wir eine Reihe von BR Effekten identifiziert, die uns verschiedene Möglichkeiten aufzeigen, wie BR im Entwurf politischer Massnahmen genutzt werden kann. Diese verschiedenen Arten von BR sind allgemeingültig, treten aber mit besondererer Intensität bei der Einführung neuer Technologien auf, bei denen bei deren Markeinführung unterschiedliche Meinungen vorhanden sind, wie dies etwa bei batteriebetriebene Elektrofahrzeuge (BEV) der Fall ist. Nach einer ausführlichen Untersuchung haben wir eine Auswahl von acht politischen Maßnahmen getroffen, die die BR der Verbraucher bei der Entscheidungsfindung zugunsten einer beschleunigten Energiewende bei der Kaufentscheidung für ein Fahrzeug nutzen. Diese Massnahmen beinhalten etwa das eigene Erleben der neuen Optionen im Kontext der Entscheidungsfindung, den Kontext in dem die Entscheidung getroffen wird, die Wahrnehmung von Informationen und die vereinfachte Darstellung relevanter Informationen, wie etwa Energielabel, oder auch Preissignale (etwa Zuschüsse beim Kauf eines BEV oder einer Ladestation). Diese 8 Massnahmen wurden zu insgesamt 21 konkreten Massnahmen ausgestaltet, die sich in der Art und Weise ihrer Implementierung unterscheiden. Die Auswirkungen der Politikdesigns werden mit Hilfe von Modellen in Bezug auf die BEV-Durchdringung in der Schweizer Fahrzeugflotte und die Nutzung der individuellen Personenmobilität in der Schweiz quantifiziert. Anschliessend werden die Auswirkungen dieser 21 konkreten Massnahmen aus einer breiteren Perspektive des Schweizer Energiesystems bewertet, wobei auf reale Daten und gängige Modellierungsverfahren genutzt wurden.

Für diese Analysen wurden zwei existierende Modelle, nämlich das agenten-basierte Modell für die Nachfrage im Schweizer Mobilität Sector (BedDeM - Behavior-driven Demand Model) und das Energiesystemmodell der Schweiz (STEM) verwendet.

BedDeM ist ein agentenbasiertes Modell, das soziale, wirtschaftliche und psychologische Elemente im Entscheidungsprozess heterogenen Haushalten abbildet. Es ermöglicht so eine Analyse möglichen Reaktionen der Haushalte auf Marktänderungen oder politische Interventionen. Seine ursprüngliche Version umfasste ein detailliertes Nachfragemodell für die Wahl der Art der Mobilität. Die Möglichkeiten des BedDeM-Modells wurden in diesem Projekt erweitert, und können nun die Kaufentscheidung von Privathaushalten für Mobilitätsoptionen (Auto, GA) unter Berücksichtigung der BR der Konsumenten modellieren. STEM, ein Kostenoptimierungsmodell mit gesamtplanerischer Perspektive, wird zur Quantifizierung der Auswirkungen der politischen Massnahmen auf das Schweizer Energiesystem verwendet. Im Rahmen dieses Projekts wurde der Umfang des STEM-Modells erweitert, um acht heterogene Verbrauchergruppen, verschiedene BEV-Ladeinfrastrukturoptionen, sowie eine Mehrzieloptimierung zu integrieren. Letztere ermöglicht eine endogene modale Verlagerung im Mobilitätssektor auf der Grundlage der Preiselastizität.

Zuerst werden die ausgewählten Massnahmen mit Hilfe des BedDeM-Modell bewertet, und dabei die Reaktionen der Haushalte in Bezug auf deren Autokauf und die Mobilitätsentscheidungen bestimmt. Die Konsequenzen dieser Entscheidungen werden anschliessend mit dem Energiesystemmodell STEM quantifiziert. Beide Modelle werden iterativ gemeinsam simuliert, wofür ein automatischer Datenaustausch realisiert wurde. Für die Beurteilung der Massnahmen wurde ein Baseline-Szenario definiert, dass eine allgemeine Entwicklung beschreibt. Für BedDeM beinhaltet dieses Basisszenario Annahmen über die zukünftigen Fahrzeugmodelle und einen vollständigen Ausstieg aus der Produktion konventioneller Fahrzeuge mit Verbrennungsmotoren ab dem Jahr 2040. Aus Sicht des gesamthaften Energiesystems zielt das Basisszenario (Baseline) dieses Projekts im STEM Modell

darauf ab, im Jahr 2050 im gesamten Schweizer Energiesystem Netto-Null-CO2-Emissionen zu erreichen. Dieses Netto-Null-Basisszenario umfasst die bestehenden Massnahmen der Schweizer Energiestrategie 2050 (z. B. Emissionsstandards für Gebäude und CO2-Abgabe) und eine Obergrenze für den gesamten CO2-Ausstoß, um die Ziele für 2030 und 2050 zu erreichen. Der Personentransportsektor in STEM ist fixiert basierend auf den Entscheidungen welche aus dem BedDeM-Modell eingespeist werden. Hingegen werden andere Sektoren in STEM aus gesamtplanerischer Perspektive optimiert, d.h. die Gesamtkosten des Energiesystems werden minimiert.

Im BedDeM werden den Agenten keine individuellen Beschränkungen auferlegt, die von einer Netto-Null Strategie abgeleitet sind. Die Baseline ist nicht normativ, da sie von 2020 bis 2030 Bottom-up-Entscheidungen sammelt, ohne Einschränkungen auf Systemebene zu erzwingen, und die Verbraucher in den Jahren 2030 und 2040 mit Brennstoffpreisen versorgt werden, die sich aus der STEM-Optimierung ableiten. Es beinhaltet aber keine Zwänge für die Individuen eine Klimaneutralität zu erreichen.

Wesentliche Ergebnisse

Im Basisszenario erreicht der Anteil von BEV an der gesamten Fahrzeugflotte 17% im Jahr 2030 und 83% im Jahr 2050. Diese Ergebnisse werden mit den Szenarien verglichen, die sich aus jedem der 21 konkreten Massnahmen ergeben, d.h. wie die jeweilige Massnahme die Ergebnisse verändert.

Kurzfristig (2030) erhöhen fast alle Massnahmen die Marktdurchdringung von BEV, dies zwischen 3% und 23% gegenüber dem Basisszenario. Die Massnahmen führen auch zu einer starken Nutzung des öffentlichen Verkehrs und der aktiven Mobilität (Fahrräder, E-Bikes, usw.).

Die durchschnittlichen jährlichen CO_2-Emissionen im gesamten Verkehrssektor werden im Jahr 2030 im Vergleich zum Basisszenario um 60.000 bis 1,1 Millionen Tonnen reduziert, abhängig von der spezifischen Ausgestaltung der Massnahmen. Die wirkungsvollsten Massnahmen induzieren hohe BEV-Verkäufe, was zusätzliche Kosten im Energiesystem verursacht, da angenommen wird, dass die notwendigen Kapitalkosten für BEVs über die Zeit weiter sinken werden, ist ihre frühzeitige Anschaffung entsprechend mit höheren Kosten verbunden, weiter fallen Kosten für den schnelleren Ausbau der BEV-Infrastruktur an. Kurzfristig verringern sie jedoch den Bedarf an CO_2 Minderungsmaßnahmen in anderen Endverbrauchssektoren (z. B. in Haushalten und Industrie). Die Gesamt-CO_2-Emissionen bleiben aufgrund der Funktionsweise des Modells gleich wie im Basisszenario, da der Kostenminimierungsrahmen von STEM kein Überschießen der Emissionsreduktion über die Ziele für 2030 hinaus ermöglicht.

Langfristig (2050) sind die Auswirkungen der Massnahmen aufgrund der Marktsättigung und der Marktannahmen (Auslaufen der ICE-Fahrzeuge nach 2040) nur gering. Nichtsdestotrotz bleiben die Auswirkungen der kurzfristigen Massnahmen langfristig spürbar und reduzieren jährlich bis zu 0,5 Millionen Tonnen CO_2-Emissionen aufgrund des frühen Wechsels hinzu BEV, der durch die kurzfristige Massnahmen erzeugt wird. Obwohl der kurzfristige Trend als positive Entwicklung angesehen werden kann, hat der Verzicht auf Massnahmen zur Energieeinsparung in Gebäuden langfristige Auswirkungen. Da das PROBOUND-Projekt sich auf den Mobilitätssektor konzentriert, wurden keine unterstützenden Maßnahmen für den Gebäudesektor angenommen. Dies führt zu langfristig höheren Kosten, weil das Energiesystem nach anderen (teureren) Abhilfemaßnahmen sucht, wenn einige der kurzfristig versäumten Gebäudesanierungen aufgrund des langsamen Gebäudesanierungszyklus nicht nachgeholt werden können. In Übereinstimmung mit früheren Studien erfordert ein Netto-Null-Energiesystem die Integration von gross angelegten PV-Anlagen, sowie Energiespeicherungsmöglichkeiten und Technologien mit negativen Emissionen.

Die wirkungsvollsten Massnahmen im Hinblick auf ihre Auswirkungen im Jahr 2030 sind die Bereitstellung von Möglichkeiten zur Erprobung von BEV (+26 % des Marktanteils), die Förderung des Schnellladens (+22 %) und die obligatorische Information bei Händlern (+6 %). Energielabels können je nach Ausgestaltung der Massnahme entweder wirksam (+4 %) oder nicht wirksam (-0,5 %) sein. Im ersten Jahr der Einführung gehören zu den erfolgreichsten Maßnahmen die die "Informationsblasen" adressieren, in denen ein Gespräch über die Vor- und Nachteile verschiedener Technologien stattfindet (+15 %), und die Verbesserung der Sichtbarkeit von Schnellladestationen durch Straßenschilder (+14 %).

Diese Massnahmen können das Erreichen des Netto-Null-Ziele erleichtern, da diese Technologien und Massnahmen bereits bekannt sind und umgesetzt werden können. Sie sind komplementär zu CO_2-Preisen basierenden Massnahmen, die in bestimmten Bevölkerungsgruppen unwirksam sind. Zusätzlich zur Verwendung des STEM-Modells für die Folgenabschätzung von BR-Massnahmen haben wir eine zusätzliche Szenarioanalyse zur Entwicklung der BEV-Ladeinfrastruktur aus der Sicht der vollständigen Energiesystemoptimierung (inklusive Transportsektor) durchgeführt bei welcher das STEM Modell eigenständig angewendet wurde. Die Ergebnisse zeigen, dass ein durchschnittliches Elektroauto etwa 5-6 kW Ladekapazität benötigt, was sich je nach Szenarioannahmen auf 1,4 - 2,3 BEVs pro privater Ladestation mit 7 kW und 15 - 65 BEVs pro öffentlicher Ladestation mit 22-150 kW umrechnen lässt. Der Zugang zu Ladestationen über Nacht sorgt für eine verstärkte Marktdurchdringung von BEVs (+31 % im Jahr 2050 im Vergleich zum STEM-Referenzszenario). Die bessere Zugänglichkeit öffentlicher Ladestationen ausserhalb von Wohngebieten macht es für Mieter finanziell attraktiver, mehr BEVs zu kaufen (+61 %), was widerum zu 66% mehr öffentlicher Ladeinfrastrukturkapazität in Wohngebieten (z. B. beim Parken am Strasenrand in einer blauen Zone) führt, um das kosteneffizientere Laden über Nacht zu ermöglichen. Während zu Hause bzw. In Wohngebieten langsamere Ladestationen (7 kW anstatt 22 kW) kosteneffizient sind da sie primär über Nacht genutzt werden, ermöglichen schnellere (leistungsstärkere) Ladestationen ausserhalb von Wohngebieten eine effizientere Nutzung von Solarstrom während des Ladens tagsüber. Eine koordinierte Strategie für die Ladeinfrastruktur könnte einen stärkeren Schwerpunkt auf Nachtlademöglichkeiten für Mieter legen und so die Einführung von BEVs bei diesen Konsumenten beschleunigen.

Dieses Projekt gibt nicht nur Aufschluss über die Wirkung und den Einfluss von politischen Massnahmen zu Effekten von BR im Schweizer Mobilitätssektor, sondern ermöglichte auch die Weiterentwicklung von zwei Analysewerkzeugen (BedDeM und STEM, einschließlich einer automatisierten Modellkopplung). Zum Beispiel ermöglichten die Erweiterungen der Verbrauchergruppe und der Ladeinfrastruktur in STEM eine detaillierte und flexible Bewertung des BEV-Ladens im Vergleich zu dem zuvor in Energiesystemmodellen verwendeten Ansatz. Ebenfalls konnte erfolgreich gezeigt werden, dass eine enge Kopplung, und Co-Simulation eines agentenbasierten Modells und einem umfassenden Energiesystemmodell möglich ist, und zu erheblichen Vorteilen bei der detaillierten Analyse komplexer Zusammenhänge führen kann. Insbesondere die Automatisierung dieser Kopplung ermöglicht, eine große Anzahl von Szenarien zu erstellen und zu vergleichen.

Der hohe Innovationsgrad des Projekts ist in zwei Dissertationen eingeflossen, deren Schwerpunkte vor allem auf der methodischen Entwicklung und deren Anwendungen befassen.

Im Projekt wurde gezeigt, dass wichtige Parameter des nationalen Mobilitätssektors und des Energiesystems der Schweiz durch politische Maßnahmen beeinflusst werden können, die Aspekte der begrenzt rationalen der Entscheidungsträger nutzen. Mit der Verbreitung dieser Ergebnisse wird das Projekt zu einer sehr wichtigen Debatte darüber beitragen, wie Erkenntnisse aus der Psychologie und anderen Sozial- und Geisteswissenschaften Modelle, deren Parameter und auch deren Ergebnisse beeinflussen können.

Die methodischen Erkenntnisse aus dem PROBOUND Projekt können auch für Analysen anderen Länder oder weiterer Sektoren übertragen werden.

Résumé

Le projet PROBOUND vise à comprendre la rationalité limitée dans le secteur de la mobilité et étudie un ensemble de politiques nouvelles, tirant parti de la rationalité limitée des consommateurs, et leurs architectures multiples. Ensuite, les impacts de ces politiques sont quantifiés à partir du système énergétique suisse dans la perspective de atteindre émissions nettes nulles au 2050.

A travers une revue de la littérature, nous identifions un certain nombre de directions de rationalité limitée (dans la suite : BR, selon l'expression anglaise "Bounded rationality") qui s'appliquent globalement mais avec une intensité particulière dans le cas de technologies totalement nouvelles avec des opinions divergentes autour d'elles, comme les véhicules électriques à batterie (BEV). Après une exploration originale approfondie, nous avons présélectionné un ensemble de politiques BR, focalisés sur l'expériences personnelles p.ex. de conduite, le contexte médiatique de jugements, la perception, l'information simplifié des étiquettes énergétiques, mais aussi des politiques qui donnent des signaux de prix (sous forme de subventions pour l'achat de véhicules électriques et pour les bornes de recharge). Huit politiques BR sont articulés et conçues en 21 architectures différentes, et leur impact sur la mobilité des passagers en Suisse est évalué. La sélection de ces politiques BR tient compte de la flexibilité des outils analytiques proposés dans ce projet. Nous utilisons deux modèles analytiques existants, à savoir un modèle basé sur les agents (BedDeM) du secteur de la mobilité suisse et un modèle du système énergétique de la Suisse (STEM).

BedDeM est un modèle basé sur les agents capturant la prise de décision sociale, économique et psychologique dans des ménages hétérogènes, ce qui permet une analyse de leurs réponses potentielles aux changements de marché ou de politique. Sa version initiale couvrait un modèle de demande détaillé pour le choix du mode de mobilité. Cette portée du modèle BedDeM a été étendue pour inclure la décision d'achat d'une voiture afin que l'effet des politiques BR puisse être évalué. Le STEM, qui est un cadre de modélisation d'optimisation des coûts du point de vue du planificateur social, est utilisé pour quantifier l'impact des politiques de RB du point de vue du système énergétique suisse. Dans ce projet, la portée du modèle STEM a été élargie pour inclure huit groupes de consommateurs hétérogènes, une gamme d'infrastructures de recharge pour les BEV et une optimisation multi-objectifs. Ce dernier permet un changement de modèle endogène dans le secteur de la mobilité basé sur l'élasticité-prix.

Tout d'abord, les politiques BR sélectionnées sont évaluées avec le modèle BedDeM, puis leur impact, c'est-à-dire les décisions d'achat et d'utilisation de voitures, est quantifié avec le modèle de système énergétique STEM. Nous avons développé un algorithme automatisé pour échanger des données entre les deux modèles et les co-simuler de manière itérative.

Pour comparer les effets et les impacts des politiques de BR, nous établissons un scénario de base. Pour BedDeM, le scénario de base comprend les annonces des fabricants au thème de leurs nouveaux modèles, avec une élimination complète des moteurs à combustion interne conventionnels à partir de 2040. Du point de vue énergétique systémique, en STEM, le scénario de base vise à atteindre l’objectif d’émissions nettes nulles d'ici 2050. Il comprend les politiques existantes de la stratégie énergétique suisse 2050, telles que les normes d'émission des bâtiments, une taxe sur le CO_2 et un plafond sur les émissions totales de CO_2 pour atteindre les objectifs de 2030 et 2050. Le secteur de la mobilité personnelle dans les STEM est fixé aux décisions du modèle BedDeM tandis que d'autres secteurs sont optimisés du point de vue d'un planificateur social, c'est-à-dire en minimisant le coût total du système énergétique.

Dans BedDeM, les agents ne se voient attribuer aucune contrainte individuelle dérivée des émissions nettes nulles. La ligne de base n'est pas normative, en ce sens que de 2020 à 2030, elle recueille des décisions individuelles sans imposer de contraintes au niveau du système et qu'en 2030 et 2040, les consommateurs reçoivent des prix du carburant qui découlent de l'optimisation STEM mais rien qui les force aller individuellement à la neutralité climatique.

Principaux résultats

Dans le scénario de référence, la part des voitures BEV dans le parc automobile total atteint 17% en 2030 et 83% en 2050. Ces résultats sont comparés aux scénarios résultant de chacune des 21 architectures de politiques de BR, c'est-à-dire comment l'intervention particulière modifie-t-elle les résultats.

À court terme, presque toutes les politiques BR ont des effets positifs et augmentent la pénétration des BEV entre 3 et 26 points de pourcentage, à partir de la ligne de base en 2030. Ils induisent également une plus forte utilisation des transports en commun et de la mobilité douce. La réduction moyenne des émissions annuelles de CO_2 en 2030 par rapport au scénario de référence est entre 0,06 à 1,1 million de tonnes, selon la politique et sa architecture, dans l'ensemble du secteur des transports. Les politiques BR les plus percutantes induisent des ventes élevées de BEV, ce qui entraîne des coûts supplémentaires dans le système énergétique en raison des achats de BEV au cours des décennies où ils représentent encore des coûts d'investissement relativement élevés (par rapport aux décennies suivantes) et à l'expansion rapide de l'infrastructure BEV. Cependant, ils réduisent le besoin de mesures d'atténuation du CO2 dans d'autres secteurs d'utilisation finale (par exemple, les secteurs résidentiel et industriel) à court terme. Les émissions totales de CO_2 restent les mêmes que dans le scénario de référence en raison du fonctionnement du modèle, puisque le cadre de minimisation des coûts des STEM ne permet pas de dépasser la réduction des émissions au-delà des objectifs de 2030.

À long terme (2050), l'effet des politiques de BR est négligeable en raison de la saturation du marché et des hypothèses du marché. Néanmoins, l'impact des politiques BR à court terme continue de se faire sentir à long terme et réduit les émissions annuelles de CO_2 d'environ 0,5 million de tonnes, grâce aux achats de BEV engendrés par les politiques au début de la periode. Bien que la tendance à court terme puisse être considérée comme une évolution positive, le fait d'éviter les mesures d'économie d'énergie dans les bâtiments a un impact à long terme. C'est-à-dire, dans le projet PROBOUND, qui a un focus spécifique sur la mobilité, il n'y a pas des politiques de soutien dans le secteur des bâtiments. Le coût du système énergétique va s'accroitre parce que le système recherche des mesures d'atténuation coûteuses, car certaines des rénovations de bâtiments manquées ne peuvent pas être compensées. Conformément aux études antérieures, le système d'énergie, pour atteindre les émissions nettes nulles en minimisant les coûts, nécessite l'intégration de PV à grande échelle avec certains stockages et les technologies d'émissions négatives.

Les politiques les plus impactantes, au regard de leurs effets en 2030, sont la mise à disposition d'opportunités d'essais sur la route de BEV (+26% de part de marché), le soutien à la recharge rapide (+22%), l'information obligatoire chez les concessionnaires (+6%). Les politiques d'étiquetage énergétique peuvent être efficaces (+4%) ou non (-0,5 %), selon l'architecture de la politique.

Au cours de la première année d'introduction, les politiques les plus réussies incluent la pénétration de «bulles informationnelles», où une conversation sur les avantages et les inconvénients des différentes technologies a lieu (+15%), et l'augmentation de la visibilité des bornes de recharge rapide grâce à des panneaux de signalisation sur la route (+14%).

Ces politiques peuvent accélérer la réalisation des objectifs zéro net, car ces technologies et mesures sont déjà disponibles et peuvent être mises en œuvre. Elles complémentent les politiques fondées sur le prix du carbone, qui sont inefficaces pour certains segments de la population. Compte tenu de l'importance de l'infrastructure de recharge pour tout scénario d'électrification des transports, en plus des co-simulations avec BedDeM, une application autonome du modèle STEM, c'est-à-dire, du point de vue d'un planificateur social, sur le développement de l'infrastructure de recharge BEV. Les résultats de cette ligne d'enquête montrent qu'un BEV moyen a besoin d'un chargeur d'environ 5,5 kW, ce qui peut se traduire par 1,4 à 2,3 BEV par chargeur privé de 7 kW et 15 à 65 BEV par chargeur public de 22 à 150 kW, selon les hypothèses du scénario. L'accès de nuit aux bornes de recharge permet le plus fort déploiement de BEV (+31% en 2050 par rapport à un scénario de référence). Une meilleure accessibilité des bornes de recharge publiques en dehors des zones résidentielles rend financièrement plus attractif pour les locataires d'acheter plus de BEV (+61 %), ce qui entraîne à son tour une augmentation de 66 % de la capacité de l'infrastructure de recharge publique dans les zones résidentielles (par exemple, le stationnement en bordure de rue dans une zone bleue) pour permettre une recharge de nuit plus économique. Alors qu'à la maison et dans les zones résidentielles, les bornes de recharge plus lentes (7 kW au lieu de 22 kW) sont rentables car elles sont principalement utilisées la nuit, en dehors des zones résidentielles, les bornes de recharge plus rapide (plus puissantes) permettent une utilisation plus efficace de l'énergie solaire pendant la charge de jour. Une stratégie d'infrastructure de recharge coordonnée pourrait mettre davantage l'accent sur les options de recharge de nuit pour les locataires, accélérant ainsi leur adoption du BEV.

Enfin, ce projet donne non seulement un aperçu de l'effet et de l'impact des politiques de RB dans le secteur de la mobilité suisse, mais il facilite l'avancement de deux outils analytiques, y compris une itération de modèle automatisée. Par exemple, les améliorations du groupe de consommateurs et de l'infrastructure de charge dans STEM ont permis une évaluation détaillée et flexible de la charge BEV par rapport à l'approche précédemment utilisée dans les modèles de systèmes énergétiques. En termes de stratégie de modélisation et d'outils raffinés, la co-simulation étroite d'un modèle à base d'agents avec un modèle de système énergétique complet, avec toutes ses difficultés techniques, s'est avérée faisable. Il a permis de générer et de comparer un grand nombre de scénarios. Le haut niveau d'innovation du projet a été intégré dans deux thèses de doctorat, dont l'accent est principalement mis sur le développement méthodologique et leurs applications.

Il a été démontré que les paramètres clés du système national de mobilité et du système énergétique de la Suisse sont influencés par des politiques et des conceptions s'appuyant sur une prise de décision socio-cognitive rationnelle limitée individuelle. Avec la diffusion de ces résultats, le projet va contribuer à un débat très important sur la manière dont les connaissances de la psychologie et d'autres sciences sociales et humaines peuvent influencer les structures, les paramètres et les résultats des modèles.

Les leçons méthodologiques de PROBOUND peuvent être utiles pour analyser d'autres pays et secteurs.

Summary

The PROBOUND project aims at understanding Bounded Rationality (BR) in the mobility sector and investigates a set of policies (and their multiple designs), leveraging consumers' BR in their decision making for personal mobility. The impacts of those BR policies are quantified from the Swiss energy system perspective while reaching Net-Zero emissions by 2050.

Through literature review, we identify a number of BR effects, which provide us different BR directions regarding which policies can be designed. Those BR directions apply overall but with special intensity in the case of novel technologies with divergent opinions surrounding them, such as Battery Electric

Vehicles (BEV). After extensive original exploration, we shortlist a set of eight policies leveraging the BR of consumers for the goals of the energy transition, targeting driving tests and other personal experiences surrounding or preceding the decision-making process, the judgmental context, the perception, the simplified information delivered by energy labels, as well as price signals (in the form of subsidies for the purchase of electric vehicles and for charging stations). Within the eight policies, we design and test 21 designs of those policies, differing in their parametrization. The effects of the policy designs are quantified with models in terms of BEV penetration in Swiss car fleet and usage of personal passenger mobility in Switzerland. Subsequently, the impacts of these 21 BR policy designs are assessed from a broader Swiss energy system perspective, drawing on real data and common modeling practices.

For this analysis, we use two existing analytical models, namely an agent-based model of Swiss mobility sector (BedDeM - Behaviour-driven Demand Model) and an energy system model of Switzerland (STEM - Swiss TIMES Energy system model).

BedDeM is an agent-based model capturing social, economic and psychological decision-making in heterogenous households, which enables an analysis of their potential responses to market or policy changes. Its initial version covered a detailed demand model for mobility-mode choice. This scope of the BedDeM model has been extended to include car purchasing decisions, opening the way for BR to influence also such decisions. The STEM, which is a cost optimization modelling framework from social planner's perspective, is used to quantify the impacts of the BR policies on the Swiss energy system. Within this project, the scope of STEM has been expanded by including eight heterogeneous consumer segments, various BEV charging infrastructure options, and a multi-objective optimization. The latter enables endogenous modal shift in the personal mobility sector based on price elasticities.

Firstly, the selected BR policies are assessed with the BedDeM model and then the impacts of these BR policies, i.e., implication of car purchase and mobility usage decisions, are quantified with the energy system model, STEM. Thus, both models are iteratively co-simulated and we have developed an automated algorithm to exchange data between the two models.

For the impact comparison of BR policies in the Swiss energy system, we define a baseline scenario. For BedDeM, this Baseline scenario includes car manufacturers' upcoming vehicle models and a complete phase out of conventional internal combustion engine cars from year 2040. In STEM, the baseline scenario from the energy system perspective constrains to achieve net-zero CO_2 emission across the entire Swiss energy system in 2050. It includes existing policies of the Swiss energy strategy 2050, such as building emission standards and a CO_2 levy and a cap on total CO_2 emission to meet the 2030 and 2050 targets. The personal mobility sector in STEM is fixed to the decisions from the BedDeM model while other sectors are optimized from a social planner's perspective, i.e. minimizing the total energy system cost.

In BedDeM, agents are not given any individual constraint derived from net zero. The baseline is not normative, in the sense that from 2020 to 2030 it collects bottom-up decisions without forcing system-level constraints and that in 2030 and 2040, consumers are provided with fuel prices that do derive from STEM optimization but nothing that force them to go individually to climate neutrality.

Main findings

In the baseline scenario, the BEV share in the total car fleet reaches 17% in 2030 and 83% in 2050. These results are compared with the scenarios resulting each of the 21 BR policy designs, i.e. how does the particular intervention changes the outcomes.

In the short term (2030), almost all BR policies increase the penetration of BEV between 3% and 23% from the baseline scenario. The BR policies also induce a high use of public transportation and slow mobility (bikes, e-bikes, micro-mobility tools, etc).

The average yearly CO_2 emissions in the entire transportation sector are in 2030 reduced by 60,000 up to 1.1 million tons, relative to the baseline scenario, depending on the specific BR policy design. The most impactful BR policies induce high BEV sales, which incurs additional costs in the energy system due to BEV purchases in decades where they are still a relatively high capital costs (with respect to later decades) and to rapid expansion of BEV infrastructure. However, they reduce the need for CO_2 mitigation measures in other end-use sectors (e.g. residential and industrial sectors) in the short term. Total CO_2 emissions remain same as in the baseline scenario because of the way the model works, since the cost minimization framework of STEM does not enable overshooting of emission reduction beyond the 2030 targets.

In the long term (2050), the effect of BR policies is subtle because of market saturation and market assumptions (phaseout of ICE cars after 2040). Nevertheless, the impact of the short-term BR policies continues to be felt in the long term and reduces annually up to 0.5 million tons of CO_2 emissions, due to the early BEV stock turnover generated by the short-term BR policies. Though the short-term trend can be seen as a positive development, avoidance of building energy conservation measures has long-term impacts. That is, as for the PROBOUND project that focussed on the mobility sector, no supporting policies for the building-sector have been assumed. Thus, costs in the long-term increase because the energy system seeks other (more expensive) mitigation measures when some of the missed building renovations in the short-term cannot be reinstated due to the slow building renovation cycle. In line with earlier studies, a net-zero energy system requires integration of large-scale PV with energy storages and negative emission technologies.

The most impactful policies, in terms of their effects in 2030, are the provision of opportunities for driving trials of BEV (+26% in market share), support to fast charging (+22%), mandatory information at dealerships (+6%). Energy labeling policies can be either effective (+4%) or not (-0.5%) depending on the BR policy design. In the first year of introduction, the most successful policies include the penetration of “information bubbles”, where a conversation about pros and cons of different technologies takes place (+15%), and increasing the visibility of fast charging stations through road signs (+14%).

These policies can accelerate reaching the net zero goals, as those technologies and measures are already available and can be implemented. They complement carbon price-based policies, which are ineffective in certain segment of the population. Given the importance of charging infrastructure for any scenario of electrification of transport, in addition to the co-simulations with BedDeM, a standalone application of the STEM model, i.e., from a social planner’s perspective, on the development of BEV charging infrastructure. Results of this line of enquiry show that an average BEV needs of about 5.5 kW charger that can be translated to 1.4 - 2.3 BEVs per private charger of 7 kW size and 15 - 65 BEVs per public charger of 22-150 kW size, depending on the scenario assumptions. Overnight access to charging stations enables the strongest BEV deployment (+31% in 2050 compared to a reference scenario). Better accessibility of public charging stations outside residential areas makes it financially more attractive for renters to buy more BEVs (+61%), which in turn leads to 66% more public charging infrastructure capacity in residential areas (e.g. street side parking in a blue zone) to enable more cost-efficient overnight charging. While at home and in residential areas slower charging stations (7 kW instead of 22 kW) are cost-efficient as they are primarily used overnight, outside residential areas faster (more powerful) charging stations allow for more efficient use of solar power during daytime charging. A coordinated charging infrastructure strategy could place a greater focus on overnight charging options for tenants, accelerating their BEV uptake.

This project not only sheds insight on effect and impact of BR polices in the Swiss mobility sector, but it facilitated the advancement of two analytical tools (BedDeM and STEM, including an automated model iteration). For example, the enhancements of consumer group and charging infrastructure in STEM allowed detail and flexible assessment of BEV charging compared to the approach previously used in energy system models. In terms of modelling strategy and refined tools, the tight co-simulation of an agent-based model with a comprehensive energy system model, with all its technical difficulties, has been demonstrated to be feasible. It has allowed a large number of scenarios to be generated and compared.

The high level of innovativeness of the project has been incorporated in two PhD theses, foci of which are mainly on the methodological development and their applications.

Key parameters of the national mobility system and energy system of Switzerland have been demonstrated to be impacted by policies and designs drawing on individual bounded rational socio-cognitive decision-making. With the diffusion of these results, the project is going to contribute to a very important debate on how insights from psychology and other Social Sciences and Humanities can influence model structures, parameters, and results.

The methodological lessons from PROBOUND can be useful to analyse further countries and sectors.

Acknowledgements

Within the project, an advisory board is commissioned with the following members. The project team acknowledge the participation and support of the advisory board members. The advisory board helped the project team in the identification and selection of BR policies to consider. However, final responsibility for choices remained on the project team. We are particularly grateful for their support. Members of the advisory board are mentioned in alphabetic order (of their last names).

- Luca Castiglioni (SFOE)
- Wolfgang Elsenbast (SFOE)
- Alois Freidhof (SFOE)
- Nicole Mathys (ARE)
- Marcel Sturzenegger (Canton SG)
- Hans Werder (Avenir Mobilité)

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Contents

Abbreviations

List of used abbreviations:

BEV – Battery electric vehicles

CHF – Swiss Franc

CO_2 – Carbon dioxide

ICE – Internal Combustion Engine

KPI – Key performance indicator

LC100 – 100% low carbon (net-zero) scenario

MJ – Mega joule

Mt – Million tons

NET – Negative emission technologies

PJ – Petra joule

pkm – personal kilometer

PV – Solar Photovoltaic

Rp – Swiss Rappen (Swiss cents)

STEM – Swiss TIMES Energy system model

Syn. – Synthetic (fuels)

TW – Two-wheelers

TWh – Terawatt hour

vkm – vehicle kilometer

wrt – with respect to

SHEDS – Swiss Household Energy Demand Survey

SFOE – Swiss Federal Office of Energy

FSO – Federal Statistical Office

IEA – International energy Agency

BAFU – Swiss Federal office of Environment (Bundesamt für Umwelt)

BedDeM – Behavior-driven Demand Model

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1 Introduction

This document is the final report of the project PROBOUND (Promoting the energy transition by leveraging bounded rationality and appropriately redesigned policies) funded by the Swiss Federal Office of Energy (SFOE) within the Energy–Economy–Society (EES) research program. We present the project aim, analytical methods, results, and policy insights.

PROBOUND investigated the presence of bounded rationality (BR) in households taking energy-related decisions. We focused on the Swiss mobility sector and explored BR policies that aimed at facilitating the energy transition. We quantitatively evaluated their effects through the co-simulation of two models: BedDeM (Behavior-Driven Demand Model) and STEM (Swiss TIMES Energy system Model). Several policies turned out to be quite effective and would deserve consideration in policy-making.

1.1 Background

Bounded rationality (BR) is a theoretical construct of many authors (e.g. H. Simon, D. Kahneman, A. Tverski, R. Thaler, D. Ariely) enjoying vast empirical support and being at the core of behavioral and evolutionary economics (Nelson and Winter, 1982; Nelson et al., 2018), as well as agent-based computational economics (Tesfatsion and Judd, 2006). The notion covers a number of different aspects in influencing decision-making, with the communality of deviating from the well-established notion of rational decision-making. In the literature, a number of phenomena are grouped under BR, e.g. emotional and affective decision-making (Achar et al, 2016; Jobin et al., 2019), multi-stage decision-making processes (Schrift et al., 2018), heuristic decision-making (Blasch et al. 2019), habits (Doyle et al. 2016), social norms (Litvine and Wüstenhagen, 2011), prospect theory, including loss aversion and endowment effect (Hoffmann and Thommes, 2020), bandwagon effect (Fuglsang and Eide 2013; Roy et al, 2013; Hahnel et al., 2020), confirmation bias (Schrackmann and Oswald 2013), mental accounting (Hahnel et al., 2020), illusory truth effect (Hasher, Goldstein, and Toppino, 1977), egocentric bias (Ross and Sicoly, 1979), availability bias (Tversky and Kahneman, 1973). Many specific, even anecdotal, pieces of evidence of deviation from rationality are covered. However, their combined effects are never assessed quantitatively, particularly at a national level.

PROBOUND turns this large body of research into a novel direction by tight co-simulation of an agent-based simulation model (operating on individual decision-making of demand by considering emotions, habits, and social factors) and a cost optimization model of the whole Swiss energy system - with high level of technology/vehicle representation and a hard sector coupling of energy supply and demands. The introduction of co-simulation approaches, where strengthens of existing modeling and simulation approaches are combined is a rather new approach to energy modeling and only a few solutions[1] exists typically coming from the research community. The combination of BedDeM and STEM represents a particular case, as it is not focusing on models of technical components of the energy system, but addresses behavioral and economic aspects. In that sense it combines micro-economic behavior modeling of household demand, with a macro modeling approach of a social planner. Due to its co-simulation type of interactions, it represents therefore one of the closest forms of how these two modeling approaches can be combined, while maintaining their particular strength.

[1] see e.g. Mosaik https://mosaik.offis.de/

We primarily focused on the Swiss personal mobility – an area where BR and information imperfections are particularly pervasive, as decisions are made on the level of deeply heterogeneous individuals and households. This means that policies are difficult to be communicated to and acted upon by consumers. This partially explains why the mobility sector remains one of the most challenging sectors (generating about one-third of the total CO_2 emissions in Switzerland) for the transition to net zero emission goals. Therefore, this area provides the most suitable testbed for assessing the effects of BR on energy-related decision-making processes and for their implications in terms of policy design.

The project goes beyond the conventional qualitative based investigation of BR issues and their consequences for policy design by carrying out a quantitative model-based assessment of their impacts on the entire energy system. It provides energy system level analysis that complements more traditional psychologically oriented research. We identified a number of BR policy recommendations that leverage BR, widen the policy toolbox and sharpen current designs.

1.2 Objectives

The objective of PROBOUND is threefold:

1. to identify specific BR in personal mobility and assess their impacts on the system level;
2. to improve current analytical power of existing models by enhancing them and co-simulating them. We enhanced and co-simulated an agent-based model, focusing on decision-making at the household level, applying a decision-making scheme originating from psychology) and a cost optimization model of the whole Swiss energy system with full sector coupling;
3. to provide recommendations for the design of policies, so that BR effects are explicitly considered and used to promote the policies' effectiveness.

1.3 Overarching methods

The PROBOUND project is a research project leveraging together the approaches, resources and models of two teams at the HES-SO Valais/Wallis and at the Paul Scherrer Institute. In particular, it tightly co-simulates two models: BedDeM and STEM. The former contains a few thousands agents, individually modelled, whose decisions are aggregated by summation to generate national values. The latter considers Switzerland at the national level, with some new level of consumer heterogeneity by cluster (not at the individual level), detail charging infrastructure, etc. As BR characterizes individuals their decision-making, its implementation is mainly in BedDeM. This model does not contain optimization at system level, which rather characterized in STEM. During the project the scope of STEM has been extended to include a non-cost-only parameters for a multi-objective decision-making. In other terms PROBOUND fosters a hybrid approach by which system-level rationality and multi-objective optimization characterize the overall energy system and its centralized decision-making (in the logics of the social planner), with the exception of mobility where decentralized decision-making is integrated.

The project has followed the sequence indicated in the following Figure 1:

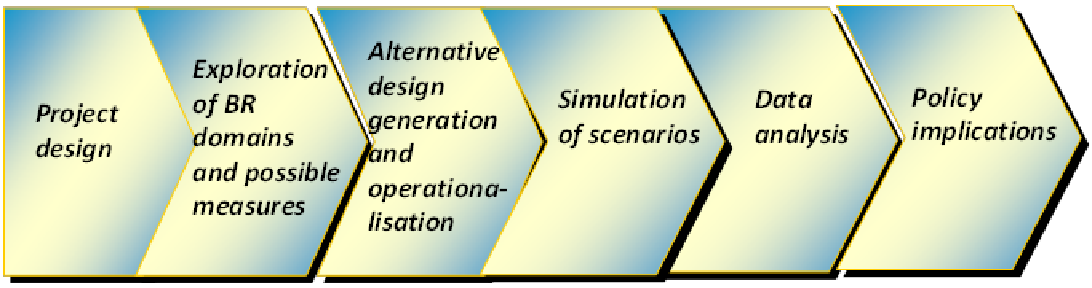

Figure 1: The PROBOUND phases

Across time, the two models have been alternating in producing a trajectory of values 2020-2050, thus achieving tight co-simulation.

STEM, the Swiss TIMES Energy system Model, developed at the PSI-EEG, is a technology-rich, cost optimization model of the Swiss whole energy system (Panos et al., 2021; Kannan et al., 2022). The model optimizes technology and fuel mix to meet the given energy service demands based on competing energy pathways while fulfilling energy supply and environmental constraints. It sheds powerful insights on long term development of the Swiss energy system. The transport sector in STEM has an extensive type of vehicles with a combination of different drivetrains and fuels. For any emerging vehicles such as fuel cell and battery electric cars, an aggregate infrastructure is included for both private and public transportation. The scope extension of the STEM model is elaborated in Section 4.2.

BedDeM, the Behavior-driven Demand Model, developed at SILab (HES-SO VS), is an agent-based model of the Swiss population, embedding a psychologically realistic human decision-making model (Nguyen and Schumann, 2018; Bektas, Nguyen, Piana, and Schumann, 2018). With it, we addressed particular BR instantiations of high importance in the mobility area. The model development during the PROBOUND project is described in Section 4.1.

We established an interface for data exchange during the co-simulation, providing the technical foundations for the inclusion of bounded rationality and for the data generation. PROBOUND explored many possible policy approaches that could leverage bounded rationality, finally operationalizing 8 policies, articulated in a total of 21 designs (see Section 3). To assess the direct and sole impact of the policies, it has obtained a baseline where all elements are in place, except the policies. For the baseline and all the designs, the agent-level, mobility-sector level and energy-system level decisions and consequences have been quantified, with trajectories, in particular, for the sales of new vehicles of private mobility, the stock of private vehicle fleet, the passenger km and vehicle km made across all different modes (private and public modes). The effects of the policies and their designs has been assessed using such indicators, as well as in relationship to mobility sector and energy sector CO_2 emissions and costs.

The PROBOUND project, on a background of an even wider range of policies, has quantitatively evaluated the impacts of the following eight policies, which are described in Section 7 (also see Table 2):

1. Interaction with information bubbles
2. Support for fast charging stations
3. Support for home/shopping/work charging stations
4. Visibility of charging stations on road
5. Energy labelling
6. Mandatory information at car dealers
7. Trial driving/using EV, micro-mobility and GA
8. Subsidy for EVs

These policies aim to address touchpoints of a bounded-rational process of car purchase which extends over time, is triggered by objective and subjective factors, and can lead not only to purchase a new vehicle but also a new mobility resource (such as the General Abonnement travel card to public transport). Some policies draw on nudging, others are independent from it.

Within the models and the assumptions of the project, these policies show different effectiveness: several of them are quite effective in the short term to boost sales of electric vehicles and to increase the use of public transport. Some of them anticipate to 2035 the year in which the fleet is composed by a majority of BEV, from the 2041 of the baseline. In 2050, they reduce the 17.2% of residual ICE vehicles of the baseline to a share within a range between 9.3% and 15.6%, depending on the policy.

The earlier and stronger penetration of BEV in the Swiss vehicle fleet reduce mobility-related CO_2 emissions. Particularly, the bounded-rational polices on EV drive trials and financial support for charging station induce the highest CO_2 mitigation. Such policies demonstrate their potential to reduce CO_2 emissions of about one million tons per year in the period of 2024-2036 compared to the Baseline scenario. The fleet's share of BEV in 2030 increase to 34% compared to 17% in the Baseline. Though BR polices directly enabled BEV in transport sector, they also impact on other sectors, what can be observed due to the co-simulation between BedDeM and STEM.

In summary: Our results indicate, as it could have been expected, that price signals, such as subsidies to upfront costs, are effective in modifying purchases and behaviors. However, we can also observe non-price based policies can have effects in about the same order of magnitude for Switzerland, as it happens with personal trials and mandatory information at dealerships.

This result is a major contribution to the debate on policies for the energy transition. Our results enable to widening the discussion of future policy design, which can consider both options as valid and effective. This potentially allows tailoring policies better and also increasing their acceptance. However, our insights are obtained quantitatively within a model, not in an experiment with people – and would probably need several of them to be qualified and confirmed. Also we exclusively focus on changes in the mobility sector, thus, discuss polcies for this sector in isolation, which of course, limits interpretatability regarding their costs for example.

1.4 Report structure

The Section 2 provides the literature and arguments on the presence and effects of bounded rationality in the mobility sector in Switzerland, preceded by a more general consideration of bounded rationality. In Section 3, we describe how the models of PROBOUND captured some of such directions and how they developed them in an original way. A brief description of the models and, especially, of their technical developments is presented in Section 4 (with a longer description in the Annex 14.4.1-14.4.3). For the ease of data flow, a clear description on how the co-simulation works is laid down in Section 5.
In the two years of the project, there has been an extensive and iterative exploration of possible policies leveraging bounded rationality, which has involved the Advisory Board of the project. In Section 6, some of the discussions are reported, leading to the selection and operationalization of policies and their designs in Section 7. In it, the reader will find an extensive description of the policies and designs, encoded with an acronym that will be used in the later session. The definition, assumptions and quantitative features of the resulting baseline up to 2050 is in Section 8, together with some comparison with other scenarios and real data. The analytical results of the policies are included in Section 9 that provides a comparative picture across all of them. The discussions of the results are in Section 10, covering in particular the implication of a high electrification trajectory, which are the most desirable policy designs, and the limitations of the study. The conclusion of the scientific part of the project is in Section 11.

The list of published papers funded by the PROBOUND project is in Section 0, while further indications are provided in Annex (14.3). The Annex has the details on technical descriptions, in which the model development and their interface are described. The extensive bibliography of the main text is in Section 13. A further bibliography is at the end of Annex section 14.4.

The lessons learned from PROBOUND for the co-simulation of the Swiss energy system are in 14.4.5.

A concise and communicative document about "Redesigning policies in a bounded rationality framework" is provided at the end, at page 109.

2 Bounded rationality in the Swiss mobility system

Bounded rationality is an overall interpretation of human behavior and decision-making, encompassing low-involvement and high stakes decisions, across all fields of life and the economy. Although often detected and underlined in institutional and business decision-making (Simon,1950; Cyert and March, 1963), including with the concept of "business routines" (Lazarik 2011), in what follows we concentrate on bounded rationality of people, consumers and households. Psychological and individual cognitive and emotional limits to the search, evaluation, elaboration, interpretation, and utilization of knowledge (information and values) lead to the tendency to simplify, constrain, routinize, and imitate from others the choice set, the way in which it is used and the final actual result of choice. Post-purchase experience (and in general any experience gained personally) reshape judgements and preferences[2]. Actions are taken when a certain threshold of activation is exceeded (Koehler & Harvey, 2008), with markets exhibiting changes only when a relatively large number of consumers shift their decisions (Piana, 2003).

Bounded rationality is covered by an extensive literature (for a synthesis see Viale, 2021; for a simple introduction to cognitive biases see Pohl, 2004; for nudging see Thaler and Sunstein, 2009; De Luigi et al, 2020; Chapman et al., 2021; Mertens et al., 2022; notable positions in the energy, environmental and climate policy: Van den Berg, 2007; Piana et al., 2009; Maréchal and Lazaric, 2010).

Hafner et al. (2017) states that

> *"using simplifying heuristics is a relatively common response to the problem of information overload, although not a 'rational' response to decision making, in the sense that a perfectly rational decision-maker would make decisions based upon the assigned expected utilities of all possible outcomes. Research has shown that creating a more manageable number of options (perhaps by quickly narrowing down the field with heuristic strategies) can in fact increase satisfaction with the chosen product".*

In specific reference to car purchase, their paper states:

> *[the] "top two most important factors when deciding which car to buy consistently involved practical and financial considerations. This is entirely in line with previous research into car purchasing decisions, and suggests these two criteria are used as a means of establishing an 'initial consideration set' of feasible options which are then subject to detailed consideration".*

Below these top two reasons, their paper found a significant role for Image and Emotion and that

> *"[t]his appears to be in line with dual process theories of judgement under uncertainty demonstrating the simultaneous contribution of automatic and non-conscious processing strategies within this decision context. Our finding that Image and Emotion play a crucial role during decision making is in line with a substantial body of previous empirical research. For example, Heffner et al. (2007) found that a key factor driving decisions to purchase hybrid electric vehicles is a desire to communicate information about one's social identity – for example to be seen as an 'intelligent moral person who cares about others'".*

In particular, advertising is an area of contested interpretation between bounded rationality and neoclassical rationality. For the former, advertising helps shaping the preferences of the consumers, impacts the short list of products that are considered in each category of goods, brings to saliency

[2] See for instance the phenomenon of buyer's regret in the case of car purchase (Keaveney, 2007).

certain features of the products while relegating others to the background, provides triggering factors for awareness and action, as well as several other roles (Piana, 2005). For the latter, the given preferences of consumers cannot be modified by advertising, which thus cannot play any influential role in decisions where only preferences, the budget constraint and prices play a role. Accordingly, the empirical extensive evidence that companies invest large sums in advertising is interpreted not in respect to consumer's behavior but rather in the interplay of oligopoly companies, e.g. wanting to demonstrate commitment not to exit the market (Tirole, 1988). Accordingly, only the level of advertising expenditure matters for the latter strand of research, whereas the former is interested to the contents and style of advertisement to elicit what the industry believes being relevant factors for decisions and good arguments in discussion in the media.

More in general, bounded rationality consumer theory shares many tenets with the science of marketing, by which consumers can be induced to make a purchase depending on a marketing mix and marketing strategies and tools. The main difference is that marketing has a goal of actually changing the sales of products and services, whereas the consumer theory brought forth in the paradigm of bounded rationality does not side with the sellers but maintain a neutral point of view.

Heterogeneity among agents can refer to the initial assignment of different values to the parameters of the agents, but more importantly regarding their objective function. So while heterogeneity of agents is not specific for bounded rationality (as also rational consumers can have different utility functions) it has to be stated that in the modeling of bounded rationality, the number of parameters that influences the agent’s behavior is growing. Thus, by the number of variables among which agents can be differentiated is larger, typically not only resulting in a theoretical larger space for potential heterogeneity, but also factually, the heterogeneity among agents can be considered larger in agents capturing bounded rationality.

In the mobility sector[3], bounded rationality encompasses both the daily decisions of modal choice for trips and the infrequent decisions of investing into a mobility resources, such as a vehicle or a General Abonnement to public transport. In the first sphere, habits play an important role in modal choice in Switzerland (Bektas, Piana, Schumann, 2021), in addition to costs and time. Social traits such household structure, employment status and level of education are found to be significant in the explanation of mobility resource ownership (Kowald, Mathys et al., 2017).
Large heterogeneity in Swiss trains users has been demonstrated by Maione et al. (2018); for instance, certain people, loving silence, obtain higher utility by segregating in a dedicated section of

[3] The mobility sector has been selected for the PROBOUND project because of its likely proneness to bounded rationality and because it represents the first source of GHG emissions in Switzerland. Please note that bounded rationality and related policies have been explored in agent-based models also of other parts of the energy system, such as electricity generation (Barazza and Strachan, 2020), energy retrofitting of buildings (Poorthuis, 2022), covering the overall energy system (for a review of 61 agent-based studies addressing climate-energy policy aimed at emissions reduction, product and technology diffusion, and energy conservation see Castro et al. 2020) as well as key components in integrated assessment models for climate mitigation (Giarola et al., 2022). The latter states:

> *"the modelling community has an open and urgent request for tools capable of more realistic interpretation of the energy transition, capturing human behaviour, and embodying the principles of transparency, reproducibility, and flexibility of use"*
> and offers a
> *"new agent-based model [which] supports flexible characterisation of agent decision-making, including individual goals, bounded-rationality, imperfect foresight, and limited knowledge during the decision process" (Giarola et al. 2022, p.1)*.

the train instead than a common one, but others do not exhibit such higher utility, as measured during the experiment. More in general, the paper, drawing on further literature, states, at p.1286, that:

> *Travelers are heterogeneous and differ on a multitude of dimensions, such as their behaviors on the train, their needs or their trip purposes.*

Public transport operators have systematically recognized the cognitive burden for potential uses of a complex time-table and have been acting upon this recognition, typical of bounded rationality, to simplify as much as possible not only the actual use of public transport but also all information, cognitive and emotional contexts. In Switzerland, they adopted a very regular schedule, with stops at the same minute each hour (and with a set step between trains), as well as the coordination between trains stops and bus services. Apps have been developed and shared with the public to simplify awareness, routing, scheduling, access, ticketing and utilization of the public transport. In these apps, many default values are set, in line with prospect theory (Kahneman and Tversky, 1979; Barberis, 2013), which, among others, underline a bias in favor of the status quo and the relevance of choice architecture (Johnson et al., 2012; Bothos et al., 2013).
As of the mode of biking, it has been underlined the importance of safety (both on the road and from theft) as important determinant of the use, in line with a multi-criteria decision-making. This also applies to e-bikes (Schepers et al. 2014; Hertach et al., 2018; Fishman & Cherry, 2016).
For sharing systems of bikes in Switzerland, the key role of communication and partnerships has been highlighted (Audikana, Kaufmann et al., 2017). Overall, it has been assessed that full deployment of biking mode could lead to a decrease of up to 17.5% of the fossil fuel-based emissions (Bucher et al., 2019).
The purchase of a car involves large sums, considerable technical and economic risk, and is carried out infrequently. These aspects contribute to make it a high-stake decision, where a full-fledged process of decision-making takes place. However, also in such process, the overall bounded rationality of consumes play a structuring role. In particularly, the huge variety of brand, models, and variants of the same model, leading to more than 1000 alternatives listed in the AutoKatalog for Switzerland[4] does not translate into actual sales for all of them. For instance, in 2021 only 406 models had positive sales, only 243 sold more than 100, and the top 50 selling models constitute the 53% of the market (our elaboration on data AutoSchweiz[5], 2021). These results points to a decision-making process in which the majority of models are simply ignored and an actual search (e.g. involving visiting dealers) is restricted to relatively few models per group of consumers[6].

For Switzerland, a modelling exercise drawing on empirical data, published in two papers (Mueller & de Haan, 2009; de Haan, Mueller and Scholz, 2009) describes the purchase of passenger cars with multiple attributes (2,089 versions varying in size, engine power, fuel type, emission characteristics, price, etc.) by consumers (40 groups varying in socio-demographic features) in Switzerland as a two-stage bounded rational decision-making process. Castro et al. (2020) comments on this modelling exercise:

> *"Individual choice sets are constructed based on previously owned cars; and alternatives are selected using a multi-attributive weighting rule. Decisions involves the perception of money based on prospect and mental accounting theories, resulting in, among others, gains and*

[4] https://automobilrevue.ch/katalog/
[5] https://www.auto.swiss/category/statistik/
[6] The market share by brand exhibits an even higher concentration, to the effect that the car market must be interpreted as an oligopoly and not as perfectly competitive. Two technically equivalent cars can be sold at very different prices because of their brand and details that would be ignored in a technical consideration but turn out to matter to real consumers.

losses being reference-dependent, and consumers being more sensitive to fees than to rebates of the same magnitude (reflecting loss aversion). Inclusion of these details of bounded rationality, possible due to the ABM approach, cause model predictions to be closer to observed market outcomes than those of traditional models. The model can study detailed policies under differentiated consumer segments and for a wide range of technical car features. This involves comparing a measure of forecasted new passenger car sales under reference (business-as-usual) and policy simulations".

Rational purchasers of vehicles should recognize the full Total Cost of Ownership, keeping in the comparison of the most "economic" model not only the upfront prices but also future maintenance and fuel costs and ownership taxes. However, according to Hagman (2020):

> *"only a small minority (4 %) of mainstream vehicle buyers conducted a complete TCO analysis and that the majority (58 %) did not calculate any ownerships costs into their vehicle choice process. In addition, vehicle buyers have a poor understanding of on-going vehicle ownership costs of their present vehicle. Thus, they are uninformed about vehicle costs in general and of TCO in particular. Calculating TCO is a challenging task for consumers, requiring both cognitive efforts and time. It can be suspected that vehicle buyers instead use purchase price as a proxy for TCO".*

In line with mental accounting[7], separating the upfront cost from future ownership taxes, which can be differentiated by emission level, would justify the empirical result for Switzerland of a very low elasticity to bonus-malus schemes at cantonal level and the corresponding high (Alberini and Bareit, 2019)[8]. Dealers have been highlighted as critical in the decisions of purchasers up to be a key touchpoint for choices including on electric vehicles (Plananska, 2020). As for the latter, their relative novelty can lead to lack of information, Rorschach-test-like projections, and even "myths". According to the UK Government's Go Ultra Low campaign, as reported by Blinkcharging, (2020)[9]:

> *"90% of Americans and Europeans believe electric cars have poor acceleration… 42% of British motorists believe an EV cannot be driven through a car wash".*

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[7] Mental accounting is the separation of current and investment costs (as well as other types of costs) in their mental representation by bounded rational consumer, to the effect that the accounts are not summed up and, for instance, certain types of incomes are directed to certain types of purchases, without pooling in the general budget (Thaler, 1998). Mental accounting has been suggested to hold also for energy (Hahnel, Brosch, Piana et al. 2020).

[8] Alberini and Bareit (2019) states:

> *"The model […] predicts that imposing a malus on cars with sufficiently high CO_2 emissions rates (over 200 g/km, or 10% of the new cars) does reduce the sales of such cars and the associated emissions. The effect, however, is very small and results in minimal reductions in the CO_2 emissions rates from new cars in the cantons that adopt the malus policy. Because of the relatively low elasticity of sales with respect to the registration fee or total annual costs, the malus actually raises cantonal revenues. The opposite is true for a bonus, which — at least in canton Geneva — reduces CO_2 emissions by a lesser extent than the malus.The emissions reductions from a malus would come at a high cost — over 800 CHF/ton. Taken together with the modest reduction in CO_2 emissions, this suggests that individual canton policies focusing on vehicles registration have limited potential".*

[9] https://blinkcharging.com/fact-from-fiction-the-real-reason-why-consumers-dont-buy-electric-vehicles/?locale=en

In response, manufacturers have addressed these myths, for instance with places where EV are washed[10] and with advertising[11]. in certain media myth busting articles have been published[12].

The real and psychological phenomenon of "range anxiety" has been indicated as a key obstacle in the adoption of electric vehicles (Biresselioglu et at. 2018; Mellinger et al. 2018). In particular, there is a vicious cycle between "range anxiety", rooted in a skeptical view on the availability of public charging, leading to the requirement of extremely large batteries, which in turn makes the EV particularly expensive and increases the time to charge, which often the non-buyers evaluate from 0% to 100%, whereas actual EV users tend to mainly utilize the range 20%-80%. It has been demonstrated that systematic underestimation of the compatibility of battery ranges with annual mobility needs can be counterbalanced by a scalable behavioral intervention (Herberz, Hahnel and Brosch, 2022).

It has been suggested by Hinnüber et al. (2019) that

> *"short test drives with BEVs are a suitable means to support the widespread promotion of electric cars… the results showed that perceptions, in terms of acquisition costs and acceleration/driving pleasure in particular, are developing positively. Other increasing values are maintenance and energy costs, engine/battery reliability, range in km, and driving comfort. In addition, the perception of all other performance factors has developed positively. Also, willingness to buy a BEV increased after the short test drive".*

This specific result has not been replicated in Switzerland, in an experiment reported by Brückmann (2022). The debate continues (see e.g. Herziger and Sintov, 2023). Irrespective of the results, in a bounded rationality perspective there is the theoretical possibility of instability of consumer preferences, subject to personal experience, in line with e.g. Jensen et al. (2013). The impact of labels has been studied by Moresino (2019) and Codaglione et al. (2016).
The relevance of awareness and information on electro-mobility has been underlined in the SCCER CREST White paper "Schweizer Energiepolitik zwischen Bund, Kantonen und Gemeinden: Zentralisieren, dezentralisieren oder koordinieren?" (Thaler et al., 2019)[13]. In the practitioners' community, behavioral economics is beginning to be utilized for consulting purposes (Fehr, 2018). In the modelers' community, bounded rationality has been recognized in agent-based models that have been used to simulate trip-level and resource-level decision-making for Switzerland (Bektas, Piana and Schumann, 2018; Scherr et al., 2020; Axhausen, 2022). Some of the actions included in the

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[10] https://www.hyundaimotorgroup.com/story/CONT0000000000011956
[11] See e.g. https://www.youtube.com/watch?v=ikIfvn5YRWE&t=170s .
[12] https://crackingenergy.com/blog/ev/guides/busting-the-biggest-ev-myths-on-world-ev-day-2021 https://www.ev-resource.com/myth-evs-are-worse-for-the-environment.html https://www.ev-resource.com/myth-evs-arent-good-for-emergenciesevacuations.html https://www.ev-resource.com/myth-it-takes-weeks-or-months-to-cross-the-us-in-an-ev.html. For a paper analysing media contents, BEV adoption and potential policies see Debnath et al. (2021).
[13] Thaler et al. (2019) states:

> *"Informationsdefizite bei der Elektromobilität: Eine repräsentative Umfrage zeigte, dass bislang nur 11 % der Schweizer Bevölkerung wissen, dass Elektroautos vom Kanton gefördert werden und sich nur 10 % proaktiv über bestehende Anreize informieren (Cousse und Wüstenhagen 2018). Wissenslücken bestehen auch bei der Ladeinfrastruktur. Gerade die Kenntnis öffentlicher Ladestationen ausserhalb des eigenen Wohnkantons ist jedoch wichtig, um die Reichweitenangst zu verringern (Gamma, Stauch und Wüstenhagen 2017). Dies zeigt, dass Bund, Kantone und Gemeinden ihre Informationsstrategie dringend besser koordinieren sollten".*

Swiss Roadmap for Electric Mobility (2022 and 2025) can be justified by a bounded rationality perspective (UVEK, BFE and ASTRA, 2022).

The descriptive relevance of bounded rationality has an impact on policy-making that would like to address real humans. As Li (2017, p. 58) states:

> *"behavioural uncertainties cannot be safely ignored in policy design… in all but the most repressive regimes, governments often have comparatively little influence over individual choices made by private citizens about what products they choose to purchase and use in their daily lives. This introduces significant uncertainties into decarbonisation pathways that are related to consumer behaviour in areas such as homes (e.g. building heating) and personal mobility (particularly road transport)"*.

3 The implementation of bounded rationality in the PROBOUND project

The PROBOUND project is a research project leveraging together the approaches, resources and models of two teams at HES-SO Valais/Wallis and at the Paul Scherrer Institute. In particular, it tightly co-simulates two models: BedDeM and STEM. The former contains a few thousands agents, individually modelled, whose decisions are aggregated by summation to generate national values. The latter considers Switzerland at the national level, with some new level of consumer heterogeneity by cluster (not at the individual level), achieved during the project. As bounded rationality characterizes individuals their decision-making, its implementation is mainly in BedDeM. This model does not contain optimization at system level, which rather characterize STEM. During the project STEM has been extended to include a non-cost-only optimization, leading to multi-criteria decision-making.
In other terms, PROBOUND fosters a hybrid approach by which system-level rationality and multi-criteria optimization characterize the overall energy system and its centralized decision-making (in the logics of the social planner), with the exception of mobility where decentralized decision-making is integrated.

3.1 The agent level: Agent decision-making

The version of BedDeM utilized in PROBOUND models more than 3000 artificial agents. In turn, each artificial agent in BedDeM represents a number of Swiss households, according to its representativeness in terms of socio-economic and behavioral aspects of the Swiss population.

Within each agent, two types of decisions need to be made. First, an agent decides about the usage of its mobility resources, i.e., it determines - for each trip it needs to perform - which mobility mode it will use, depending on its length, availability of certain public transport options, the speed and the comfort of the chosen means of transport. This decision-making module has been developed in previous projects, i.e. the SCCER CREST, and is re-used in the PROBOUND project. It is relevant for the project, as it first determines the usage of mobility modes, and therefore needed amounts of fuels / energy supplies required for performing the trips. Second, for the privately owned vehicles this influences the aging of the vehicle, as one of the relevant factors to replace vehicles is the driven-kilometers of the vehicle.

The second type of decision-making is on the purchase of mobility options, e.g., different types of vehicles. This type of decision-making is significantly inspired by principles of bounded rational decision-making. A key aspect of this is that decisions are not taken in the full presence of all possible existing options, thus it is a decision under incomplete information. In the following Figure 2 the process is shown, providing the broader frame in which Figures 3 and 4 zoom in.

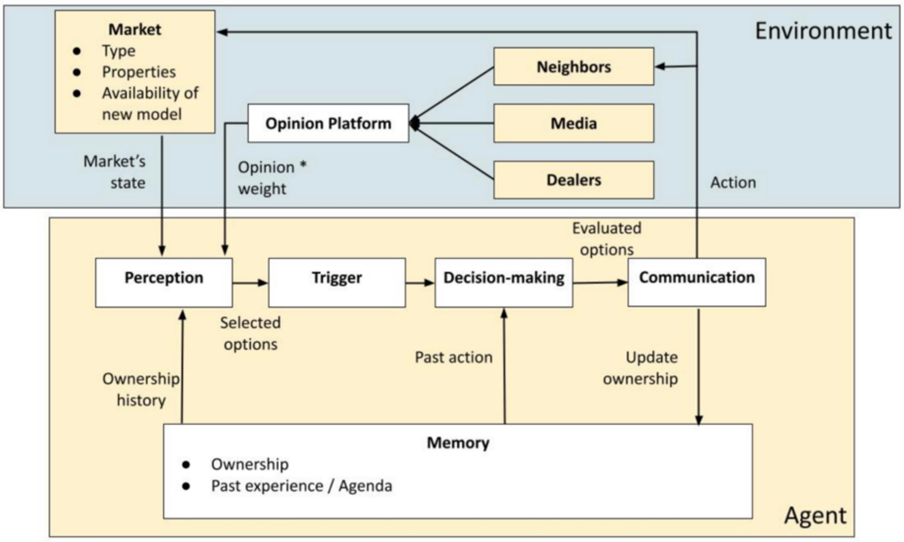

Figure 2: Overview of the agent-internal decision-making and its interactions with its environment

For the upper part of the Figure 2 (Environment), see Section 3.2. We now detail the decision-making, which is shown in the lower part of the figure above, which represents the reasoning within an agent. The first (from left to right) component gathers and filters all relevant information for the purchasing process, which is referred to as the perception module of the agent. The goal of the perception module of the agent is to mimic the effects in bounded rational decision-making, i.e., limiting the number of options available for the later selection phase. This is important, as this component defines the options among which later decisions can be made. It reduces the number of options (various vehicle brands and models) to a (typically for humans) more manageable size, by filtering. We have decided to model this perception regarding the most common criteria for filtering, which are the following:

- Engine types
- Energy labels
- Reserve price
- Brands
- Recommendations from information bubbles

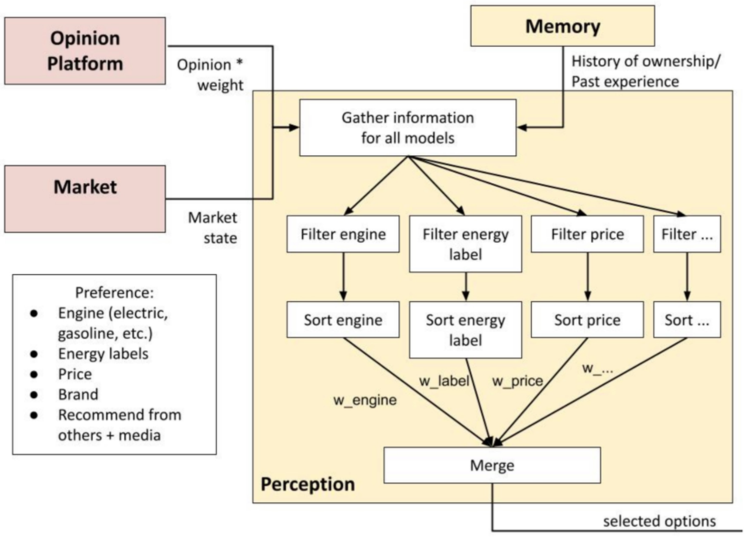

Figure 3: Schema of the triggering mechanism of a BedDeM agent.

Thus, the list of overall models in the Objective market, counting typically dozens of options, is reduced to a size of 7-10 options among which later the decision-making will happen. The overall available models will be filtered by the preferred characteristics of the agent, and therefore e.g. certain brands are excluded, as it happens with specific engine types or not recommended models of vehicles.

Of course, this filtering represents a simplification of reality. It is clear that also in human decision-making a filtering happens, the criteria to which this happens are likely more heterogeneous among individuals, and also probably not completely pre-determined, as individual circumstances can influence these filtering processes.

After the perception module has evaluated the state of the market and provides a list of potential options for a purchase, the trigger module gets activated. Within this module the decision is taken, if the particular agent will make a purchase at all at the point of time of the simulation. This reflects that vehicles are not only purchased as a pure technical replacement, but a number of households are triggered by other aspects than the pure technical breakdown of their existing vehicle. Thus, triggering is a largely deterministic process that takes the following aspects into account:

- Traveled kilometers of the existing vehicle
- Age of the existing vehicle
- Number of novel models in the market, since the last purchasing decision

If a triggering condition is meet, the agent will begin a purchasing process. This is performed in the decision-making component. Within the decision-making, one option will be chosen from the pre-selected list of options. The decision-making is considered to be more elaborated (considering more aspects and in more detail) and is inspired by a psychological theory of human decision-making (Triandis, 1977), as reinterpreted in the algorithmic scheme shown in the Figure 4.

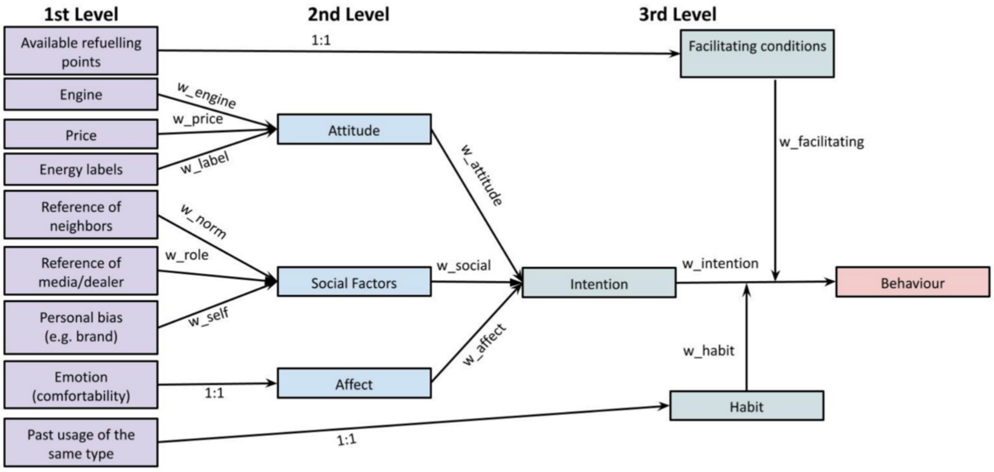

Figure 4: Schema for the multi-stage decision-making component of a BedDeM agent

The aspects considered are listed in the 1st level shown in the Figure 4 (left-hand side). All considered options are ranked according to these criteria (a ranking is made for each aspect) and individual preferences of the agent. In the following steps of the decision-making, those rankings are joined, until one absolute ranking of considered options (which determines the "best" option for the specific agent) is computed. This "best" option is then chosen by the agent and its choice is recorded for the later simulation of trips. Please note, "best" is not refering here to a cost-optimal solution, but is based on the combination of different rankings, which are performed regarding the criteria in the first level.

For the later interpretation of the effects of policies, it is worth noting that some policies will affect the criteria used for the filtering, and therefore will affect the consideration of specific models. Vice versa, a policy that is affecting other criteria than those used in the filtering, will not change the pre-selection of options. Put in simple terms, as an example, if EVs will not be considered in the pre-selection phase, a household will not buy one. It is a necessary pre-condition that households perceive EVs as a viable option to consider them for a purchase, since, if not the case, they will not appear in the decision-making process as options, and despite their performance regarding all factors relevant for the decision-making, they will not be considered.

3.2 The mobility sector level

The mobility environment is constituted by an objective market of more than 250 models, several cluster of brands (with their dealers) and a media environment, where a conversation takes place commenting and judging alimentations (ICE, BEV, hybrids, hydrogen) and brands. Topics of conversation are the price, the quality, the social image, the environmental image, the frequency of public charging and refilling stations, the time of charging / filling and, broadly speaking, myths. This approach is very flexible and allows for future integration of new topics (e.g. potential restrictions of use due to energy shortages, congestion at charging/filling stations, etc.). These topics, which are related to alimentation and brands as appropriate (not all topics are related to all possible objects of conversation), are considered in a sort of Likert-scale, with neutral value being 0.5, a zero value for the most negative assessment and a value of one for the most positive one.

Agents are heterogeneous in their exposure to different media and condense their judgements in a simplified way. Bounded rationality is thus reflected in a conversational model in which decisions are influenced by what at mobility sector level is said.

3.3 The energy sector level

Except for mobility, all other subsectors of energy production and use, as well as the overall energy system, are considered as responsive to a social planner that optimizes a social function in STEM, under the constraint of net zero emissions in 2050. This hybrid approach combines the coverage of centralized and decentralized decision-making.

4 The model developments

4.1 BedDeM model development

The BedDeM (Behavior Driven Demand Model) is a simulation platform embedding a socio-cognitive agent-based approach, built on the key theoretical tenets of multi-agent cognitive system, in which every individual agent is capable of making psycho-socially sound decisions and takes into account both objective and subjective elements (e.g. weight for evaluation criteria of alternatives) (Nguyen and Schumann, 2018; Nguyen and Schumann, 2021).

The platform has been instantiated for the mobility sector and utilized in the Joint Activity "Evolution of mobility: a socio-economic analysis" in conjunction with other models, including STEM. In that project, the modal choice at trip level was the only module. In PROBOUND a second module, with the choice of resource purchase, including a vehicle, has been developed, as described above. In this second module, the agents are potentially prone to bounded rationality policies, without predetermining how they be reacting. With a short-term decision-making part (mode-choice) and a long-term decision-making part (purchase choice), BedDeM now integrates the inter-relation between short- and long-term decision-making processes, where each process is modelled individually.

All the above model development is a part of a PhD Thesis accepted at Utrecht University (Nguyen, 2023). In parallel, the input tables for the model have been prepared, based on empirical evidence. A summary of this model's development is provided in Annex (14.1 and 14.2). Further description of the model is in 14.4.4.2.

4.2 STEM model developments

The Swiss TIMES Energy system Model (STEM) is a technology-rich, cost-optimization model of Switzerland. It is the coupled whole energy system of all end use sectors and energy conversion sectors. STEM optimizes technology and fuel mix to meet given energy service demands. 14.3.1, we highlight some key features of STEM. The STEM's transport module cover most of the Swiss passenger and freight transportation sector. It has an extensive type of vehicles technologies with a combination of different drivetrains and fuels. A summary of the transport module is provided in 14.3.2.

In the PROBOUND project, the STEM model is mainly used for assessing the energy systemic energy impacts of policies leveraging bounded rationality (BR) in the passenger transport. First, it indicates what a baseline in the passenger transport implies for the entire energy system, then it computes what else happens if such policies are implemented. The policies are described in Section 7, the data exchanges are defined in Table 2 and quantified with the BedDeM model, leading to the results presented in Section 8. There is no quantitative comparison of this bundle of simulations with a trajectory where the consumers are rational in the neoclassical sense. Within this project, the following three aspects that are specific to personal mobility are implemented in STEM:

1. Enhanced demand-side representation of mobility consumers to reflect consumer heterogeneity with socio-economic aspects and to distinguish trips by distance (described in Sections 4.2.1 and Annex 14.3.3)
2. Extensive development of electric charging infrastructure for cars (described in Sections 4.2.2 and Annex 14.3.3)
3. Multi-objective optimization with endogenous modal shift based on cross-price elasticities (described in Sections 4.2.3 and Annex 14.3.4)

The above three model developments are highlighted in the following subsections and more detail, including data sources are provided in the Annex 14.2.

4.2.1 Mobility consumers in STEM

The original STEM model has one homogenous representation of mobility consumer. We introduced eight mobility consumer groups (Figure 5) based on trip type, household income, agglomeration (based on access to public transport), household type, etc. More details are provided in the working paper in Annex 14.3.3. The primary aim of these consumer segments is to reflect heterogeneity in household mobility consumers, which are characterized by a set of mobility behavioral attributes. The consumers groups are calibrated to Swiss mobility survey data (e.g. annual drive, hourly driving patterns, car occupancy, car size, etc.). Each consumer segment can buy car technologies from a pool of vehicles differentiated by drivetrain and fuel (see Table 17). All these aspects are described in the working paper (see Annex 14.3.3).

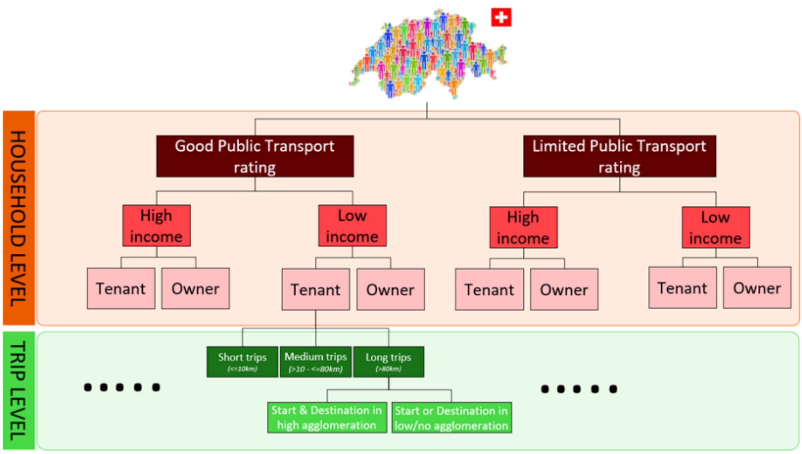

Figure 5: Representation of consumer segments in STEM

4.2.2 Electric charging infrastructure in STEM

The early version of the STEM model (Kannan et al., 2022) has very generic electric vehicle charging infrastructure. This has been extensively developed within this project to better reflect consumers' charging needs and possibilities. Figure 6 shows the schematic of the charging infrastructure that are characterized by their locations and accessibility by the different consumer group (see Section 4.2.1). The following four type of charging infrastructure are modelled:

- *Private home charging* (7 kW) that can be installed and used by consumers who park cars at own home (and own private parking lot) (called PRIV in the analysis of results in Section 9.6).
- *Publicly-owned residential home charging* (22 kW) thPat can be used by consumers who park car at own or rented public parking lot (e.g., on-street parking) (called RESID later on).
- *Public charging in commercial parking lots* (22kW) that can be used when car is parked in public parking lot, e.g., workplace, train station, and supermarket (called COMM later on).
- *Rapid public charging* (150 kW) that must be used to cover long-distance trips (called RAPID later on). Compared to the public charging, it is installed on highways and used during long distance trips that are defined as a threshold based of BEV battery range. It can also be considered as competing with commercial parking lots.

Full description of the charging station is well described (with the analytical results) in the working paper (see Annex 14.3.3). Based on this model development, we assess the role of BeV infrastructure in deployment of BeV. A working paper is included in appendix 14.3.3.

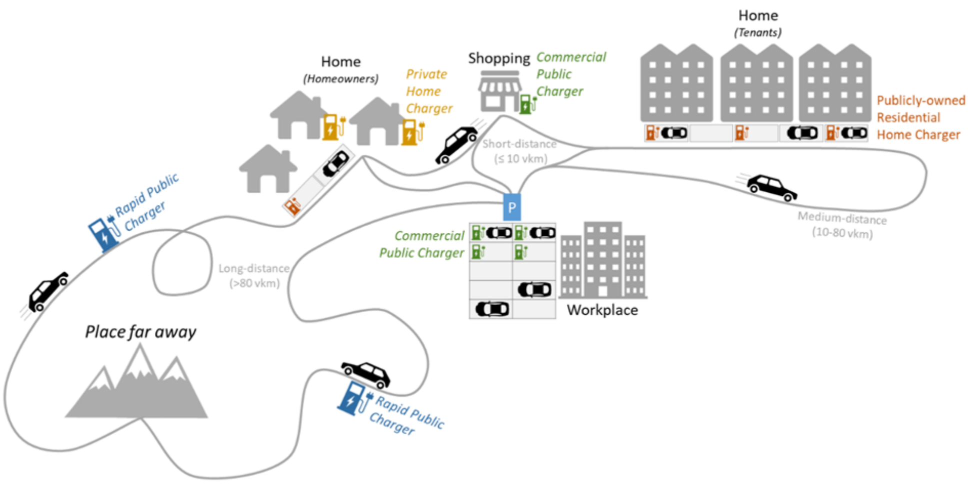

Figure 6: BEV charging infrastructure options in STEM

4.2.3 Multi-objective optimization

To enable modal shift options in STEM, we implemented price elasticity in STEM that allows endogenous modal shift when several transport modes cover the same trip types. In addition, we integrated non-cost attributes, such as comfort level in each transport mode; and travel time that represents the time spent in commuting, driving, fueling, charging, etc. Thus, STEM model can be optimized to each of these attributes. Moreover, we implemented a multi-objective optimization, which allows going beyond the traditional cost-optimizing framework of TIMES models. For the multi-objective optimization, various attributes (cost, travel time and comfort level) can be weighted into the objective function. We apply this model to assess the role of modal shift in achieving net-zero goal (under preparation, see Annex 14.3.4).

4.2.4 Application of STEM

For the co-simulation of BedDeM and STEM (see Section 5), we use the STEM model version with consumer segment and charging infrastructure. In the impact assessment of BR polies, STEM adopts the car fleet, mobility demands, and hourly driving patterns (see Section 6.2.2) from BedDeM through the co-simulation (see Section 5). The insights from the systemic energy impacts of the policies are discussed in Section 9.

In addition to the co-simulation, based on the model enhancements on new consumer segments and electric car charging infrastructure, we assess the need for BEV charging infrastructure in Switzerland from a social planners perspective. A journal paper is submitted. This paper focuses on the charging infrastructure needs to enable a cost-efficient deployment of BEV (see appendix 14.3.3).

From the third model development, i.e., multi-criteria optimization, we assess the role of modal shift in meeting the net-zero goal. A journal paper is being drafted. This paper aims to determine the systemic implications of consumers' higher or lower modal shift willingness to achieve a net-zero Swiss energy system. The paper is indicated in Annex 14.3.4.

All the above model development is a part of an ongoing PhD thesis at PSI (Luh, 2023).

5 How the co-simulation works

While in the previous Section the two decision-making schemes within the BedDeM models has been outlined, we now detail how the overall flow of simulation models is organized in the PROBOUND project. In total three simulation models are involved and need to be executed in a coordinated way. These three models are the following:

1. The BedDeM mobility mode choice model (determining household usage of mobility modes)
2. The BedDeM vehicle purchasing model (determining the purchasing decision-making)
3. The Swiss TIMES Energy System Model (STEM) that quantifies energy systemic effects of the above two decisions from the BedDeM, i.e., car purchase and usage of different mobility modes

Within the BedDeM models the agents have to be kept synchronous: the agents making decisions on mobility usage are logically identical to the agents making the purchase decisions; decisions are recorded consistently; each agent in BedDeM is encoded to belong to a STEM consumer group. Furthermore, data about aggregated demand, in total and by consumer group, need to be provided to STEM, which will determine the consequences and decisions on the energy system level.
As all these decisions are considered to be relevant with different time granularities and with different time horizons, the coordination of the different runs of the simulations, as well as a proper and automated data exchange between the models is vital. In the following we detail the overall rythm in which the simulations are executed.

BedDeM mobility mode choice model
The model is computing four representative weeks for each year. For each agent, individual trip-based mobility demands are analyzed, and decisions are taken. These representative weeks are designed based on specifics from data sources like the Mobility Micro-census. Results are later scaled up to an annual base, so each week represents a quarter of a year.

The BedDeM vehicle purchasing model
Purchasing decisions are supposed to be less frequent, and therefore each agent is executing this model twice for each year. All agents perform the perception, and evaluate if either by external conditions (e.g. market evolution) or by model internal conditions (mileage of the owned vehicle) a purchase decision gets triggered. Thus, only a rather small number of agents in each execution actually do get triggered, and therefore enter in the process of making a purchase decision (partial participation to market). Agents meet dealers twice a year, collecting some information about models and views on topics of conversation. It should be noticed that only new cars are taken into account, so the calibration of totals is to new car registrations. This is because for used cars there is a lack of

statistics, both for totals and at the model level. A discussion of the consequences of this simplification is in Section 10.4. Further limitations are discussed in Section 10.3.

BedDeM summary

For each half-year that gets simulated, the first two mode choice runs are executed, followed by one run of the vehicle purchase model. As soon as a new vehicle is purchased, it can be used by the agent.

STEM

The decision-making in the overall energy system is based on cost minimization from a social planner perspective by taking into account national level technical and policy constraints. Since STEM has 10 year time steps, BedDeM data (i.e. usage of mobility by modes and the new car fleet of by vehicle type) for each 10 years period are fed to STEM, which computes the evolution of the Swiss energy system for the subsequent next 10 year period. The resulting energy cost from STEM are provided to BedDeM (a proxy for transport fuel prices) and provide a new future timeline for following simulation runs, e.g. providing updated fuel prices, which obviously influences then the future runs of BedDeM.

Data exchange between models, as foundation of co-simulation

Table 1 show the list of key parameters exchanged between BedDeM and STEM during the iterative co-simulation. Besides, both models adopt the same car techno-economic characteristics (see Table 17). The overall time covered in the simulations, and how this is used, is shown in Figure 7.

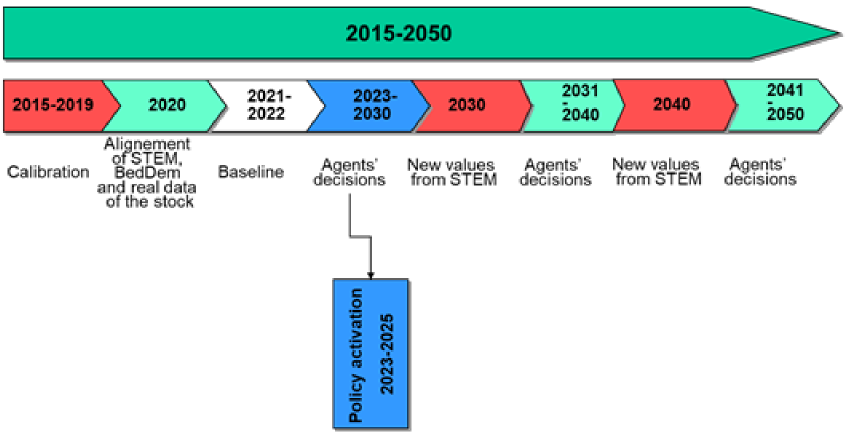

Figure 7: The tight co-simulation across one scenario over the years

The short term effects of policies are only derived in BedDeM, while the “voice of the social planner” is heard every ten years, with the typical decadal step of most long-run models of the energy system[14]. After each run of the corresponding model, the relevant generated data is extracted and transferred to the other one automatically. Similar, once data has been made available, it is processed to be integrated in the corresponding input format for the model, and the continuation of the model execution is started, also this is automated to enable for a co-similation that does not require additional human intervention.

[14] See for instance the models currently included in the CROSS project (https://sweet-cross.ch/).

Table 1: Data exchange between BedDeM and STEM for co-simulation

BedDeM to STEM	STEM to BedDeM
• New car fleet investments by car technology type and consumer segment (Million cars) • Total car stock (Million cars) • Annual mobility demand trajectories (pkm) by modes, trip types, and consumer segments • Hourly mobility demand patterns by modes, trip types, and consumer segments (pkm shares) • Hourly driving patterns of each car technology by trip type and consumer segment (pkm)	• Transport fuel cost by fuel type (CHF/PJ) • Aggregation of various Microcensus households to consumer segments

The data for years from 2020 to 2022 are the same in all the scenarios and across both the baseline and all the policy designs. In modelling terms, this integration of two models, which alternate in providing inputs to each other over a simulated time is relatively unusual and represent a clear case of simulation coordination. For this reason, the tight co-simulation of models should be considered as an important methodological result of the PROBOUND project.

The co-simulation approach allows for capturing the interaction among the micro-level and the macro-level. It is clear, that these two levels are mutually interact and influence each other. This cyclic dependency cannot be captured in a sequential execution of the two models. Thus, we have to discretize the interactions among the models during the execution of one simulation run[15].

[15] For a discussion of three ways to coordinate simulations see Section 14.4.

6 The exploration of policies leveraging bounded rationality

Taking bounded rationality into account enables to consider a wide range of policies, entering in fruitful relationship with the bounded rational decision-making process of consumers. During the PROBOUND project, there has been an exploration of such potential areas, where policies can be considered. These discussions have been taken place both internally in the research team and with the Advisory Board, to provide a broader scope. The resulting areas for policy design to potentially take advantage of BR are shown in the following Figure 8.

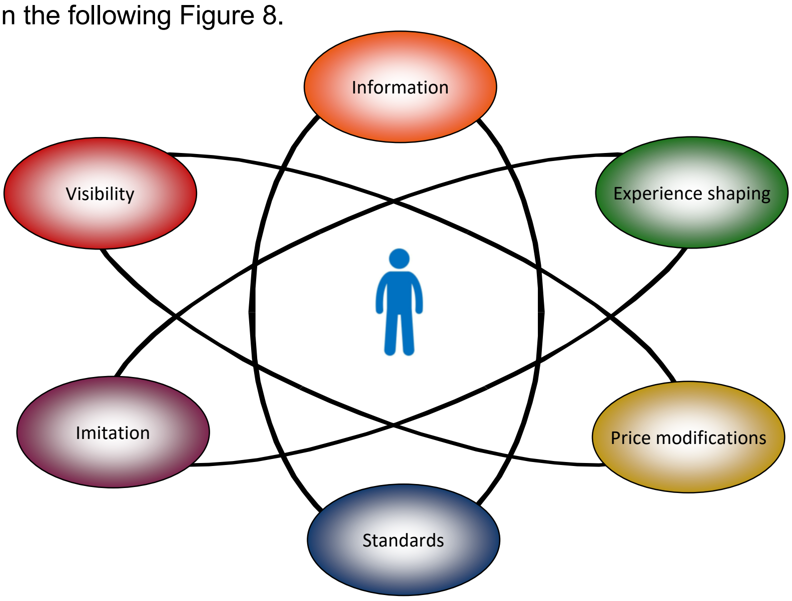

Figure 8: Domains for policies leveraging bounded rationality

The six areas include

- the provision, in locations attended by the person, of information, both in factual and judgmental terms (including mental frames);
- to make perceivable and visible (in actual spaces and places) elements that can lead to judgement (thus offering a phenomenological anchoring);
- to set the conditions for personal experience to occur and be shaped;
- to enhance the spontaneous social process of imitation of others' choices (thus leveraging bandwagon effects and processes);
- to modify the absolute and relative prices;
- to provide reference standards, hopefully leading to social norms.

A first-level operationalization of this scheme is shown in the following figure.

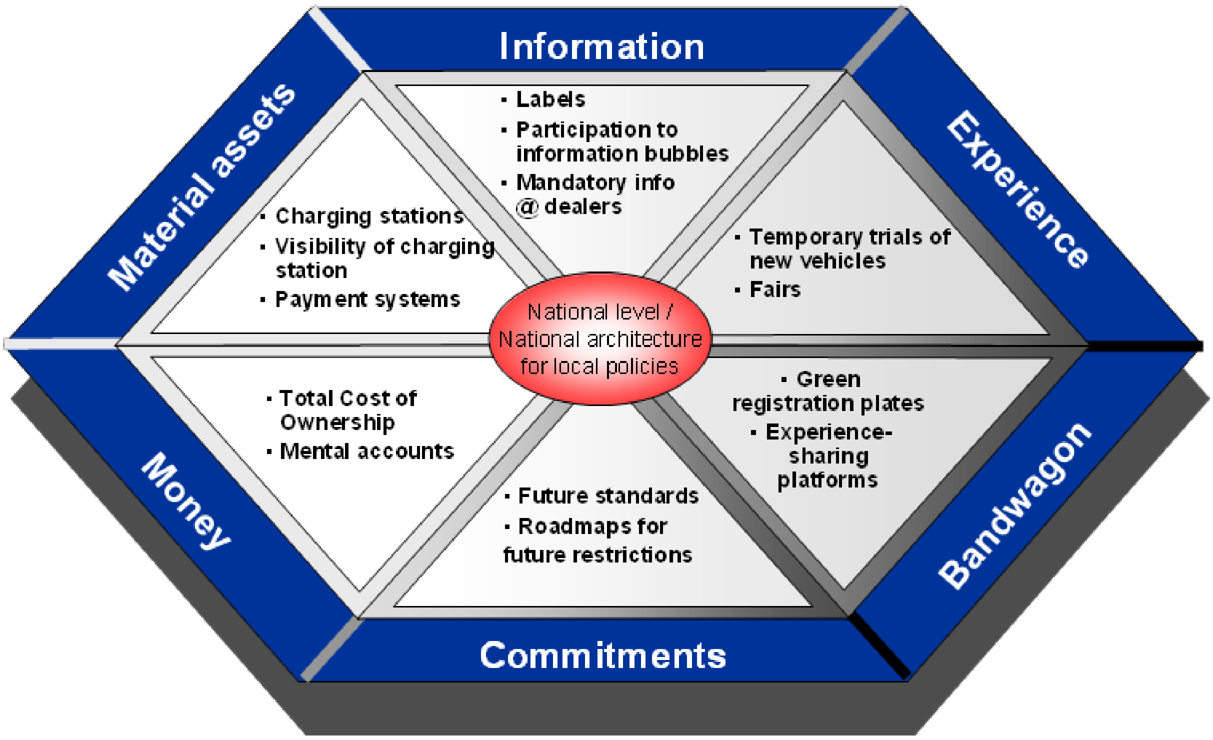

Figure 9: Articulation of domains of policies leveraging bounded rationality

Within these identified areas a list of 40 policies has been identified, which would represent potential policies, promoting a faster transition, including by accelerating the uptake of BEV by private households. These policies have been assessed along three dimensions, namely how much the item is

- promising,
- politically feasible,
- innovative.

The members of the Advisory board[16] have been asked to provide a personal independent evaluation in a scale from 0 (min) to 10 (max)[17]. The average rating and its dispersion across different people have provided a background for the successive selection process, by which the feasibility of implementation in the models has taken a central stage.

Since evidently not all items could be covered in the quantitative scenarios, we provide a concise summary of a few potentially relevant policies that unfortunately we could not include in the final set of scenarios. Those included will be enlisted in Section 7.

[16] The PROBOUND project's advisory board members are Luca Castiglioni (SFOE), Wolfgang Elsenbast (SFOE), Alois Freidhof (SFOE), Nicole Mathys (ARE), Marcel Sturzenegger (Canton SG), Hans Werder (Avenir Mobilité).

[17] Please note that the assessment of the political feasibility was totally subjective and not linked to specific experiments to test the possible support that such policies might have, as it is achieved by Brückmann and Bernauer (2020).

Mobility pricing for km made in different modes has been authoritatively suggested as key policy to change the mobility system. However, changes in prices for trips could not easily be transformed into information to be included in the total cost of ownership, because they depend on where actually the planned trips are supposed to happen. The buyer would need to forecast where he/she will be travelling over the next few years and compute the corresponding costs increase. Actually, in a bounded rational perspective, it is doubtful that this computation can be carried out and, secondly, people do not sum up costs that belongs to different categories of mental accounting (Thaler, 1998). Moreover, a central tenet of psychological pricing is that people over-react to certain presentation of prices. Our models could not be extended in a way to cover psychological pricing impacts, as this requires a carefully funded and data-based grounding.

Labels for tires could influence the choice of tires, which could increase by 10-20% the range, for the case of electric vehicle for which range anxiety is a relevant factor. Actually, the supply of EV-specific tires could have some (brand-independent) improvement of their perception[18]. However, the agents in our models do not make a specific choice for tires. Moreover, there has been a suggestion that there are already too many labels.

Local policies for the transition, including exclusive parking for electric vehicles (both with and without charging opportunity) and regulations for taxis (which would have impacted the personal experience of the passenger on a relatively wide measure), were not selected, because parking time and the use of taxi are not covered by the models. Still, it is to be underlined that such policies turned out to be very effective, in a previous extensive exploration, which already joined the PROBOUND models (as well as others) (Piana, Del Duce and Schumann, 2019; Piana, Hintermann, Burger, Farsi, Duce, Ramachandran, Darudi, Weigt, Schumann, 2020).

Future national bans of sales of certain types of vehicles and fuels have demonstrated to be very effective (e.g. in Norway) but their introduction in the models would provide to trivial result (if there is a ban, obviously consumer cannot buy, whatever their rationality) or, if one would like to see how people react in the years before the expected ban, this would require non-myopic consumers. In BedDeM consumers are myopic: they look at the current objective and perceived market and current prices. Accordingly, this policy has not been selected for implementation in models.

7 The policies and their designs as implemented in the PROBOUND models

Bounded rationality involves a multi-stage decision-making where cognitive and emotional limitations tend to reduce the number of alternatives evaluated, to simplify the way in which they are evaluated. A wide number of policies that actively address touchpoints of the overall purchasing process have been discussed in different moments of the PROBOUND project, in particular with the collaboration with its Advisory board.

[18] See e.g. Vennebörger et al. (2013). For a Swiss study on the relevance of labelling “silent” tires, see Hammer and Bühlmann (2018).

The policies and their designs that have been satisfactorily operationalized in the model, although not covering all the discussed options, and have been reduced to eight in their aforementioned assessment process. These eight different policies have been operationalized for performing quantitative evaluations. In total of 21 policy designs have been created, whereby we consider a policy design a particular parametrization of a policy. An overview of these policies is shown in the following figure.

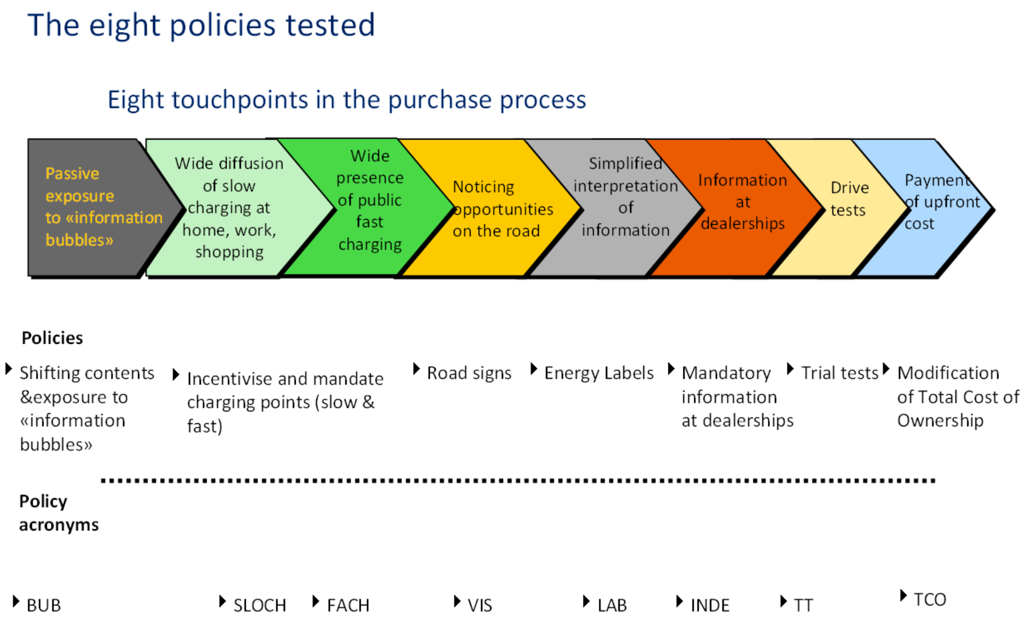

Figure 10: The eight policies tested and their touchpoints

Table 2 contains a description of the design, the type of bounded rational bias and effect on which it broadly draws upon. It indicates whether the traditional nudging techniques are involved or not and whether the design sends price or non-price signals. Further below, an extensive description of all the design follows. Later in the text, the policies will mainly be discussed using their acronyms.

Policies and designs				
	Description	**BR cognitive bias**	**Nudging**	**Price or non-price policy**
Shifting contents and exposure to "information bubbles"				
BUB1	Enhanced positive messages in the neutral oriented media	Confirmation bias	No	Non-price
BUB2	Enhanced positive messages in the positive oriented media	Confirmation bias	No	Non-price
BUB3	Minor but new presence of positive opinions in the negatively oriented media	Illusory truth effect and its demise	No	Non-price
BUB4	Strengthening exposure to positively oriented media	Confirmation bias	No	Non-price
Support for Fast charging				
FACH1	Financial support, leading to more charging in reality	None	No	Price
FACH2	National standards and financial support; leading to higher Opinions on the topics	Bandwagon	No	Price and non-price
Support for Slow charging				
SLOCH1	Charging opportunity at the home of tenants (50% of eligible population)	Availability bias	Yes	Price and non-price
SLOCH2	Charging opportunity at work (50% of eligible population)	Availability bias	Yes	Price and non-price
SLOCH3	Charging opportunity at shopping (50% of eligible population)	Availability bias	Yes	Price and non-price
SLOCH4	Charging opportunity at the home of homeowners (50% of eligible population)	Availability bias	Yes	Price and non-price
Charging stations visibility from the road				
VIS1	Visibility of DC fast charging stations from 2 km	Availability bias	No	Non-price
VIS2	Visibility of DC fast charging stations from 5 km	Availability bias	No	Non-price
Energy label policies				
LAB1	A successful communication campaign aimed at raising salience of the energy label	Salience bias	No	Non-price
LAB2	Energy label "A" is reserved for zero direct emission vehicles	Simplification	No	Non-price
Mandatory information at dealerships				
INDE1	An ordered list of emissions of all vehicles of the brand (from lowest to highest) is provided to prospective customers and signed by them	Salience bias	Yes	Non-price
INDE2	Map of charging stations	Salience bias /Illusory truth effect and its demise	Yes	Non-price
INDE3	Automatic subscription to all charging networks & payment systems	Salience bias/simplification	Yes	Non-price
Drive tests				
TT1	EV (nationally scattered) trials for three years	Egocentric bias /status quo bias	Yes	Non-price
TT2	Micro-mobility vehicles nationally scattered trials for three years	Egocentric bias /status quo bias	Yes	Non-price
TT3.	GA (nationally scattered) trials for three years	Egocentric bias /status quo bias	Yes	Non-price
Total cost of ownership				
TCO1	Subsidy to the prices of EV (costing less or equal to 23 000 CHF) by a 7 000 CHF reduction	Prospect theory	No	Price

Table 2: A summary of policy designs

Policies addressing "information bubbles"

Policies shifting contents and exposure to "information bubbles" (collectively called BUB in what follows) draw on two sources of bounded rationality. On the one hand, the "confirmation bias" is a well-known cognitive tendency to search for information sources and selection of information pieces that confirm prior beliefs (in order to avoid "cognitive dissonance", the presence of contrasting pieces of information pointing in different direction and value judgement). Whenever a doubt can be risen, it is discarded in favor of prior beliefs. For instance, people having a negative opinion of a new technology will over-emphasize any weakness and under-emphasize any strength that may be underlined by a certain information source and, even more radically, they will keep afar from sources that provide "too positive" pieces of information on that technology. On the other hand, in recent times, it has been discussed a "post-truth world", where "fake news" occupies important pieces of the public debate, which in turn is fragmented into "information bubbles" that publish only what the reader wants to listen. This phenomenon, which draws more on sociology than psychology, has been encorporated in the project, based on SHEDS data of readership of different type of media and their potential bias (Weber et al. 2017). In model's term three media sources have been included in the environment of the agent, differentiated by the presence of certain topics of conversation and for the values that certain topics referred to an object (e.g. an engine alimentation) take (more or less positive). The four designs of BUB policies cover different approaches.

- In BUB1, more positive judgements appear in information bubbles that have a balanced coverage of BEV.
- In BUB2 more positive judgements appears in information bubbles that are already quite positively oriented to BEV.
- In BUB4, such information bubbles have more readers (people exposed to).
- In BUB3, there is a minor but new presence of positive opinions in information bubbles that are otherwise negatively inclined to BEV[19].

In this design, assuming for a moment that in such media there are "myths" that border to lies, the psychological mechanism leveraged is twofold: on one hand, the "illusory truth effects" is the fact that repeated lies tend to stick and convince, for conformism (which is another bounded rationality effect for which people take the side of what they feel is the unanimous consensus), even people that in isolation would not believe them. On the other hand, it has been demonstrated that it is enough that a few dissonant voices strongly restate the truth for the demise of this effect. Please note that in this qualitative discussion we are inserting elements that are not in the model: there is no truth or lie, just values in a vector, encoding positive / negative reporting about EVs.

In these policies (BUB1-4), there are no price signals, except that these informations / attitutes might can address the cost of EV-based mobility, but this is not effecting the objective price of a specific model in the market. These policies may work before the formation of the prior beliefs, which is the main policy indication to leverage the "confirmation bias". Thus, they in principle work particularly effectively for totally new technologies and specific technological conformations. Conversely, they do not act in the saliency of a decision, thus they do not belong to what is typically considered as "nudging".

[19] For instance, they publish an article on "Now a km made in EVs costs more that in ICE" and browsing the article they quote a research study in which it is assumed that all charging is made in public fast charging (and not at home) and a lot of km are added in order to account to assumed trip deviations in order to reach "sparce" charging opportunities. Or they extensively cover the "dirty secrets" of cobalt used in batteries without mentioning that there are cobalt-free batteries.

Policies addressing the promotion of fast charging

The policies supporting the installation of fast charging (called FACH) aim not only to the objective comfort that they introduce in the actual use of BEV, but also to modify the prior belief that charging is long and difficult, kept by BEV-skeptical people. People that have a negative attitude tend to ignore certain logical links and to over-emphasize others. BEV-skeptical people over-emphasize the "range anxiety", thus setting extreme requirements (a very long range, a very large battery) to then grumble that BEV are expensive and slow to charge (and may easily negate the link between their requests and the final bill to pay). There exist small and nimble EV but they are "filtered out". Adding fast charging, which is what the FACH1 is about, provides an objective anchoring on which to build further arguments. In FACH2, the increase of stations is to fulfil a national standard, such as a fast charging every 30 km of national or cantonal road. This design matches the interest of the policymaker of not overspending for installations that would have occurred even without the support[20] and the clarity that bounded rational consumer expect from a policy message. Standards provide anchoring for expectations (in this case, people can expect that the standard is filled thus will have no problems in charging frequently, thus possibly not in full. All this would provide ground for consumers to expect a very large adoption of BEV, thus putting in motion a "bandwagon" effect. Such policies do not belong to what is typically considered as "nudging".

Policies addressing the promotion of slow charging

The policies supporting the installation of slow charging (SLOCH) aim not only to the objective comfort that they introduce in the actual use of BEV but also to provide a "default value". The "default value" is the value prevailing if no specific choice is made. For instance, a contract may dictate its automatic renewal (if not action is taken, the contract continues to hold). If it becomes a normal thing that a charging is present, for instance, in most residential building, BEV tend to become the "default value" as well. In another vein, the presence in habitual place of charging leads to the "availability bias", a mental shortcut that relies on immediate examples that come to a given person's mind to produce inertial choices, which for the purpose of this text can be considered as synonymous to "saliency bias". Supermarkets leverage the "availability bias" by placing in the most accessible places for eyes and hands the products on which they have the larger profit, relegating cheaper and less profitable versions in the lowest shelves[21]. In the different designs of this policy, the installation can happen at homeowners (SLOCH4) or at tenants (SLOCH1), which different in their size in the Swiss population and income. There are known difficulties for tenants to impose to the condo the availability of charging (and in Germany there is a relatively new regulation overcoming them[22]). With SLOCH2, the policy is directed to employers to offer charging opportunities at work (which may become part of the benefits), with significant system level advantage of charging during the day, where the expected flow of electricity from photovoltaics installation will be concentrated, instead than during the evening (when

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[20] In other terms, wherever the standard is already met today no support is provided. Where it is not, a support is provided, possibly in the form of future buy-back: the installer commits to repay the financial support - received at the time of installation - after a certain number of years, which can be correlated to expected future diffusion of BEVs (thus profitability of the charging point). This means that the policy is at zero cost for a policymaker with sufficient time horizon. It is an application of an ex-ante coordination strategy that is considered as important in the case of innovation that require complementary assets (e.g. vehicles and infrastructure).

[21] See https://medium.com/@giaphualihua/eye-level-is-buy-level-the-principles-of-visual-merchandising-and-shelf-placement-5f2fd8f7f298.

[22] Gesetz zur Förderung der Elektromobilität und zur Modernisierung des Wohnungseigentumsgesetzes und zur Änderung von kosten- und grundbuchrechtlichen Vorschriften (Wohnungseigentumsmodernisierungsgesetz – WEMoG), available at https://www.bmj.de/SharedDocs/Gesetzgebungsverfahren/DE/WEMoG.html.

people typically come back home), where the sun is not available. SLOCH3 takes a different route: it involves supermarkets, shopping centers and other commercial venues endowed with parking slots to provide (for free or for a payment) charging opportunities to clients. This abolishes the social distinction embedded in the other three designs, favors relatively short charges during which a useful activity takes place (eliminating the psychological burden of the time spent). Also shopping tend to occur in the daylight, when PV is providing supply (laterally, the carports and the roofs of the shopping venues are excellent locations for PV). Since slow charging is typically cheaper than fast charging (and can be even for free at work or at shopping), these policies contain an implicit price signal, in addition to the abovementioned non-price signals. Since they produce "acquaintance" with BEV, to some extent they can be considered as part of a "nudging" strategy.

Policies addressing the visibility of charging
Policies increasing the visibility of fast charging through road signs at a relatively long distance from the charging points (VIS) provide some comfort in the actual use of BEV (although drivers largely rely on digital apps) but more specifically are aimed for non-drivers, in order to provide phenomenological evidence of the ubiquity of charging opportunity. "Seeing is believing": people overstate their own experience in judging aggregate numbers, because of the "egocentric bias". They also normalize BEV, engendering "bandwagon" and "default value" effects. The two designs differ in the distance at which the signs begin to be put on the road: at 2 km in VIS1 and already at 5 km in VIS2. Please note that, at some Swiss highways it has been started to set-up signs (even indicating the number of charging slots). However, they are still relatively near to the place and are not spread across lateral and entry roads. Charging places outside highways are very often not signaled. In line with FACH policies, VIS do not involve nudging.

Policies addressing energy labels
Policies utilizing energy labels (LAB) are already enacted in Switzerland and abroad[23]. They are rooted in the bounded rationality effect that simple pieces of information are more utilized in real decisions than complex numerical computation, in direct contrast with what the neoclassical economics states. Moreover, what is simple in cognitive terms is more often purchased than what requires balancing pros and cons. Energy labels are a key "cognitive dissonance" in advertising of large and powerful cars, which, if ICE, emit a lot. Their advertising is typically very emphatic, suggesting power and freedom. When the eyes go to the label and see a F, they deflate the message. By contrast, the presence of an A label near an EV may provide "cognitive consonance". For the policymaker, energy labels are an elegant way to promote energy efficiency in a technologically neutral way across many product categories. A first design of this policy (LAB) consists in a wide-scale communication campaign aimed at raising the saliency of the energy label, with the effect that agents have a higher weight on this while filtering, at first, and evaluating, later on their purchasing options. Another relevant aspect is the fact that the thresholds for an "A" shift over the years, to the consequence that the consumer may have purchase what was an "A" at the time and not realize that now the same vehicle would earn a "C". Such a campaign may even trigger to take into consideration the possibility to purchase an energy-efficient substitute to what currently owned (non only in the mobility sector). The second design (LAB2) reserves the "A" label for the (Wheel-to-tank) zero emission vehicles, while shifting of all non-EV and non-hydrogen fueled cars into a B or worse category. In bounded rational terms, the policy provides a clear definition of an A label, instead of the changing thresholds which have been used until now. Please note that this policy will implicitly be adopted in Switzerland when a sufficiently large number of zero-emission vehicles will be available in

[23] See Brannigan et al. (2021) for a review and a number of related policy proposals.

the marke, because of the way in which the label is attributed. While being the “poster child” of bounded rationality policies because of their wide real adoption, labels do not rely on nudging at the point of sales, except for the fact that they are mandatory also at dealerships). As both LAB1 and LAB2 do not operate there, these designs do not rely on nudging (nor obviously on a price signal).

Policies addressing information provided by dealers

Policies mandating certain information at dealerships (INDE) rely on the importance of delivering a climate-friendly message at the topical moment of search, model comparison, and purchase. The vast majority of purchases is made in dealership (with the interesting exception of a BEV leader and some other BEV followers) and one can expect the consumer to ask there for advice, features, and to negotiate the price. Saliency is the bounded rational mechanism according to which whatever attracts attention in the actual moment of choice will have an impact of the choice itself. Again, this is at odds with neoclassical economics in which only the objective features of the elements of choice set, interpreted in the light of a subjective forward-looking utility function, can play a role.

These policies clearly insist on nudging, shaping the architecture of choice and increasing saliency of certain aspects, which are different according to the design.

In INDE1, an ordered list of emissions of all vehicles offered by the dealer (typically of the same brand but possibly covering several ones) is not only exposed but also handled to potential buyers, asking them to sign it. Signature is a very strong symbolic moment of awareness and decision. In this way, the awareness of the burden to the climate that the customer is going to inflict by his own decisions can raise the importance of this parameter in the decision-making process. Simlar, the emotions play a role in decisions, the more so if felt in the exact moment of choice. All this leads, in the model, to an increase of the weight that emissions have during decision-making.

In INDE2, the visual information exposed at dealerships is a map of charging stations. There are plenty of apps where the actual BEV driver can find such information, even in real-time (signaling which is busy and which is available). However, during a visit to dealerships in view of a future purchase, the map, which may be detailed for the canton, Switzerland and the neighboring countries, would visibly contrast the prior belief that there are no fast-charging stations, that they are not near customer’s house, that there are no free charging point, etc. Please note that SFOE already offer an online tool for this purpose[24]. The policy simply shifts the map in the exact place and time where a purchase decision is going to materialize, instead of relegating to a post-purchase low-involvement routinized issue, different every time one makes a trip.

INDE3 copes with an issue that many people not having bought an EV would typically ignore: the payment of the charging session is often cumbersome, with many non-compatible proprietary systems. Credit cards are not a common way to pay in absence of subscription to a charging network[25], which may well be free but always requiring the same personal details. This policy design relies on the well-known difference in behavior between an “opt-in” and an “opt-out” choice architecture. By being handled all the RFID cards and subscription, unless the consumer “opts-out”, this design greatly simplifies payment, boosting the number of charging point actually usable, given the subscriptions one made and sends a clear message about the issue (“Open for business 24h 7/7”). Although until now this policy is called “mandatory info”, as in its implementation in the model we consider all dealers to comply, one could also consider the intermediate step of calling dealers to a

[24] https://www.geo.admin.ch/en/news/datasetoftheweek.detail.news.html/geo-internet/2019/datasetoftheweek20191009.html under the headline: “Where can I find a free charging point for my electric car?”

[25] Charging network can have roaming agreement, usually with an extra-fee, both domestically and internationally. As with telephony, regulations on roaming can send powerful messages about the freedom of movement in a unified socio-economic space.

discussion table on good practices and build a consensus around some of these measures. INDE policies strongly implement a nudging strategy, without sending direct price signals, except for the social interpretation e.g. of free charging opportunities.

Policies addressing test trails
Policies increasing the opportunities to have a personal experience with the technology or service through test trials (TT) rely on the “egocentric bias” that lead people to give a very strong weight to their own experience. Such experience can counterbalance the media narratives and the information bubbles. Through the trial, people can verify by themselves particular “truths” and “lies” they hear in advertising and the media. They can involve their family in the decision, without the need of too many technical explanations (which are not relevant e.g. for children). These opportunities can be located away from dealership, in a brand-neutral environment, and generate experiences that can be shared with others (which become way more trustworthy than the words of an interested seller). More in general, such policies rely on the endogenous formation of preferences, which, instead of being “given” as the neoclassical theory assumes (without addressing the issue of their origin), are considered as resulting from a process in which personal experience plays a role[26]. In particular, the first design (TT1) provides driving opportunities with BEV. This is a new technology, on which exist many contrasting opinions and myths. Direct experience of e.g. acceleration would come to a big surprise to people that associate “automatic gearboxes” with slow boring driving, or the difference in comfort due to lower noise levels.
The second design of this policy (TT2) is a temporary free General Abonnement to public transport. In general, one expects the Swiss population to have strong awareness and a clear idea of the level of quality of public transport. Yet, there are still many people that are mono-modal car-centric: they dismiss public transport for any type of normal trip. They developed a specialized skill in driving, enjoy the type of “independence” that it provides and outright refuse to take a trip with other means of transportation. However, it may be possible that, given for free the opportunity to use it, they may take the opportunity and be positively surprised by what they discover in such experience.
TT3 applies the same logics to the multitudes of micro-mobility vehicles (kick e-scooters, etc.), which are very popular among the young, but raise questions (e.g. on safety) in other cohorts. The opportunity to test (and be trained) first in a protected close environment and then on the road may lead to a more positive assessment and the development of a certain “etiquette” of good manners as for the conduct, so to increase compatibility with other roads’ users.
In all these designs, what the models can operationalize is the availability for three months of the mobility resource (EV, GA, micro-mobility vehicle). This policy does not rely on nudging but on the circular flow between personal experience, skill development and enjoyment. Even if the price is temporarily zero, this is not a policy that gives a permanent price signal (the price level is ancillary to the main leverages at hand; it serves only not to exclude people from the trials).

Policies addressing monetary subsidies
Finally, a direct monetary subsidy, reducing the purchase price, is also tested. In this design (TCO1), a large subsidy (7 000 CHF) is immediately reducing the price of clean vehicles that cost 22 000 CHF or less. So, it’s quite a selective instrument, in line with more recent iteration abroad of the common policy of subsidizing (which are now often putting price ceilings). The goal is to address the need of very affordable clean alternatives and avoid that the diffusion is limited to the upper part of the market. A total of 31 models over the simulated decades are covered by the subsidy. Hybrid plug-ins and

[26] There is a consolidated stream of research on “experience goods” starting from Nelson (1970).

hydrogen vehicles are included in the instrument, but none turns out to be able to benefit from it, because of their price. Accordingly, only (some) BEV are actually covered. From a bounded rational perspective, this policy relies on prospect theory, which underlines the importance of discount from a reference point (which justifies the abundant use of percentage discount in supermarket offers, showing two prices, instead of simply stating one price, as it is the common assumption in neoclassical models[27]).

In summary, policy designs providing price signals are the following: FACH1, TCO1. Designs that send both price and non-price signals are FACH2, SLOCH1-4. All the others rely on non-price signals. In particular, nudging is at the core of INDE1, INDE2 and INDE3, SLOCH1-4, but not in the other policy designs[28].

On a more general level, the PROBOUND approach to policy design is in the following figure:

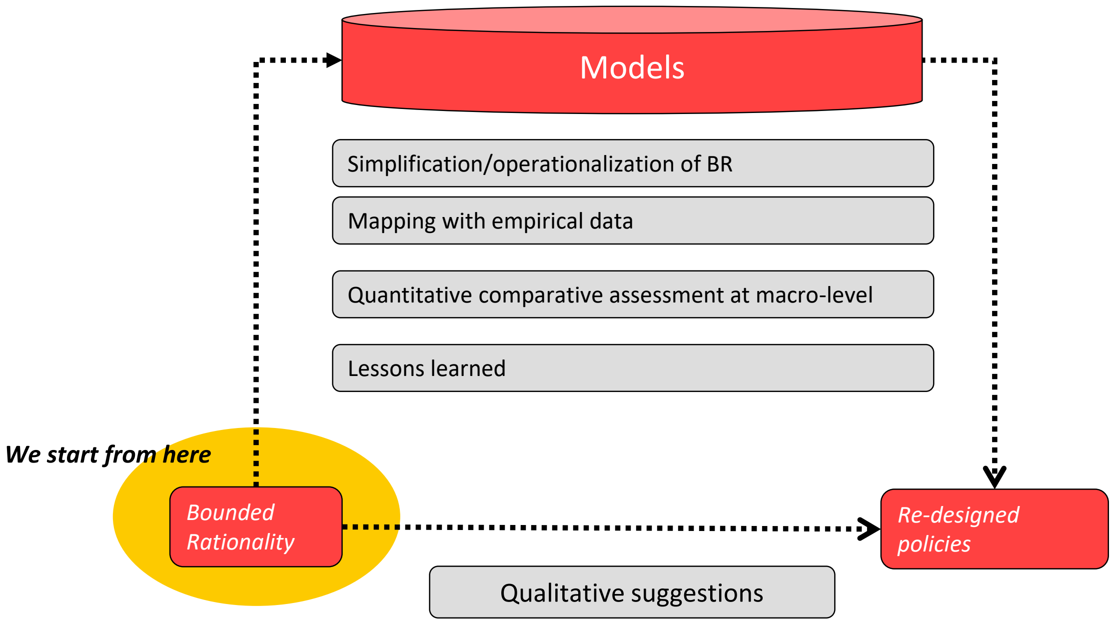

Figure 11: Schema for policy design and evaluation

In principle, it is possible to study with the models several designs at the same time and with a wide variety of temporal implementation (for instance, a design for a certain number of years and another for a subsequent period). However, due to time constraint of the project, all designs are implemented separately and have been activated for three years (2023, 2024 and 2025). As all simulations are performed until 2050, the short- as well as long-term implications of these policies can be investigated. Please note that this happens in comparison to a baseline, which is detailed in the following Section 8.

[27] For a discussion see Piana (2013).
[28] For an SFOE EES project on nudging see “Applying nudging techniques to promote fuel efficient car purchases” and its final report (Herberz et al., 2021).

8 The baseline for the quantitative comparisons

8.1 Assumptions

8.1.1 Definition of baseline

The baseline is not an extrapolation of historical data, but reflects thousands of micro-choices by agents which are aggregated by summing them up (without excluding that groups of choices are interconnected at the micro-level). Thus, it has been computed by the co-simulation of the two models.

For this computation none of the policies under investigation was enacted. However, the baseline is not a business-as-usual scenario. Within the common modeling assumptions, which are in common for all scenarios and policies evaluated, that particular developments will happen in Switzerland, not necessarily as a policy investigated here, taking advantage of BR, but out of the Swiss context, as a small national market within Europe. We assume that Switzerland will migrate to carbon neutrality until 2050, and deployment of new and emerging technologies will enable to reach this goal. Thus, in addition to the existing policies in the Swiss energy strategy 2050 (e.g. building energy efficiency standards, ETS, CO_2 tax (BfE, 2021)), new investments in low carbon technologies and fuel (e.g., in carbon capturing and storage, renewable energy, hydrogen) facilitate reaching the net-zero goal. These technologies are determined endogenously in the STEM model. Thus, prices e.g. for fuels, will be effected by this assumptions during a simulation run, effecting mode choice decision, and therefore indirect the demand for replacing vehicles. However, no other related consequences, except the price signal itself, will be effected within the agent-based decision-making of the agents.

Such an assumption has strong implications for the cross-sectoral impacts beyond mobility, whose variables are modified accordingly. For mobility, agents are not given any individual constraint derived from net zero. The baseline is not normative, in the sense that from 2020 to 2030 it collects bottom-up decisions without forcing system-level constraints and that in 2030 and 2040, consumers are provided with fuel prices that do derive from STEM optimization but nothing that force them to go individually to climate neutrality.

Overall demographic and socio-economic development of Switzerland are in line with such assumptions.

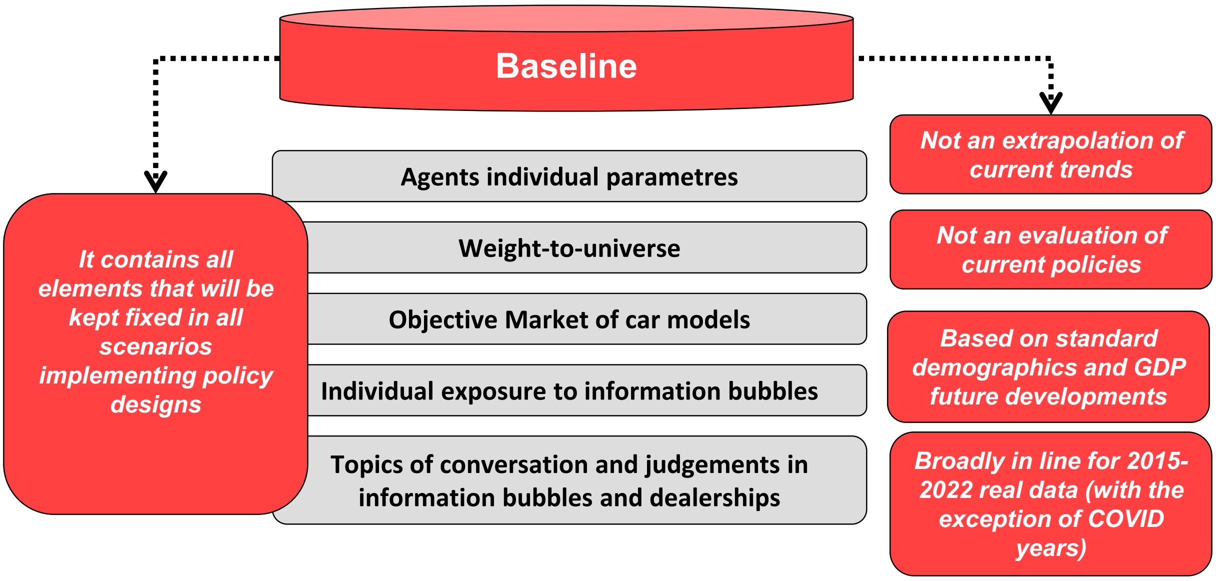

Figure 12: Summary high-level features of the baseline

When implementing mobility-related policies, the model is run again, obviously with different outcomes. The difference between those results (referring e.g. to the sales of different types of vehicles, the composition of vehicle fleet, its use and thus personal km made, etc.) are attributed to the policies, since the models are fundamentally deterministic. Agents remain the same in all scenarios: their individual parameters, which draw on SHEDS, Micro-census data as well as on calibration, are unchanged.

Please note that the baseline scenario cannot contain every possible educated guess that an informed expert would express regarding the future (which, by the way, does not need to be the same across several experts).

8.1.2 Assumptions on the objective market of supplied vehicles (2020-2050)

The objective market list of car models from which the agents can select is composed by 289 models, 114 of which are already available now and the others are coming into the market in later years. They differ in terms of alimentation, types (e.g. small, family, executive cars) and brand cluster[29]. Their price reflects real market data, since each car model is referred to a real one, typically the most sold in 2021 per type and brand cluster. For future prices, STEM provided the pathway of price percentage changes that has been applied to initial values. Models are also characterized by energy label (again reflecting real values) and comfort (with standard value per type of car). Each model has an entry year into the market and an exit year out of it.

The objective market is widened in the future years based on announced models, with the introduction of BEV, hybrids and fuel cell electric vehicles powered by hydrogen by a wider set of brands and no big novelties in ICE (e.g. in terms of comfort and prices). However, we assume that in particular in the future the number of BEV will increase, and later dominate the market. ICE continue to be offered, with their standard price modifications, until the year 2039. From 2040, manufactures, as a market

[29] This list is our elaboration drawing on the AutoKatalog by Automobil Revue, TCS verbrauchskatalog.ch and the sales statistics by AutoSchweiz.

development, stop to offer them[30]. There is currently no assumption that Switzerland will pose a ban on the sales of ICE or similar policies. However, the Swiss market will be effected by banning ICE in the European market. A minor increase in comfort is envisaged from 2035 reflecting higher degree of (useful) autonomy of the vehicles.
In the later decision-making of the agent, the objective market gets filtered by the individual agents (with some models eliminated from comparison) and ranked, with respect to individual goals and perception, shaped by the conversations going on in the media environment (which include both traditional media and dealerships).

8.1.3 Assumptions on the media and public perception environment

We use SHEDS data[31] to attribute individual exposure to media environment (real newspapers) and to categorize media in three groups (positively inclined to EVs, negatively inclined and balanced), for which a broad number of topics related to alimentation and brands are summarized in values [0, 1] (e.g. overall quality, environmental impact, availability of charging, etc.) whose weighted average influence the individual perception. The values in media judgement have been derived from textual analysis of empirically categorized media sources, based on SHEDS. An important assumption is that opinions do not evolve over time, since forecasting such changes would be very challenging and may pre-empt the policy effects.

8.1.4 Assumption on purchasing power and demographic developments

All agents have a reserve price for their purchases, i.e. a maximum price that they can afford in order to buy a vehicle. The value for each agent has been attributed based on the car model they declared to have as main family car in the SHEDS survey. Such specific model has been mapped to the objective market so that the values are compatible. The reserve price is increased every year according to standard GDP growth assumption. Similarly, the weigh-to-universe of each agent is updated yearly to reflect cantonal increases indicated by FSO.

8.1.5 The calibrated parameters at agent level

The weight system of individualized agents is derived from individual answers to questions in SHEDS and, for the remaining parameters, from a calibration process to adjust the model to the overall sums of km made in different modes between 2015 and 2019. These years are thus excluded from consideration in the analysis of results[32]. Please note that such parameters remain the same for all years and for all scenarios (so both for the baseline as for the policy designs implemented in the scenarios) throughout the entire project duration.

8.1.6 STEM assumptions

For STEM, we use the socio-economic and techno-economic drivers from the SCCER Joint Activity Scenarios and Modelling (SCCER JASM). All the assumptions are well documented and available in Panos et al. (2021). Assumptions specific to the transport sector are also described in Kannan et al. (2022). For the co-simulation, we adopted the existing net-zero carbon scenario from Kannan et al.

[30] This manufacturer's choice for Switzerland may well reflect policies abroad forbidding the sales of ICE after 2035, since the Swiss market is not large enough to guarantee profitability above the break-even point for models produced for the global market.
[31] See Weber et al. (2017) for general description of the Swiss Household Energy Demand Survey (SHEDS) and methodological explanations.
[32] For the methodological basis distributing to the micro-, meso-, and macro- level the direct input, the calibration and the validation of models see Bektas, Piana and Schumann (2021).

(2022) as the **Baseline**. Though we denote the scenario as Baseline, it is not a business as usual scenario. This **Baseline scenario aims to reach a net-zero CO_2 emission in the Swiss energy system by 2050**. The baseline scenario is primarily used for comparing the effects of BR policies (applied in BedDeM model, see Section 8.1.1). Table 3 shows the key scenario assumptions in the baseline scenario. Assumptions on energy price, technologies costs specific to the transportation sector are given in Annex 14.3.1. The baseline scenario results derived in STEM are described in Section 8.2.4.

Table 3: Overarching assumptions in the Baseline scenario

Key assumptions	**Baseline (LC100)**
Demands	Socio-economic demand drivers similar to the Swiss energy strategy 2050 plus (BFE, 2021). No new nuclear power plants, and existing plants are phased out after 60 year operational lifetime
Building emissions standards	12 kg-CO_2/m^2 in 2030 and beyond for the existing buildings New buildings 0 kg-CO_2/m^2 from 2030 and beyond
Vehicle CO_2 emissions standards	Cars: 105 g-CO_2/km in 2020 & 65 g-CO_2/km in 2030 and beyond LGV: 160 g-CO_2/km in 2020 & 110 g-CO_2/km in 2030 and beyond HGV: 680 g-CO_2/km in 2020 & 475 g-CO_2/km in 2030 and beyond Coach buses: 820 g-CO_2/km in 2020 & 575 g-CO_2/km in 2030 and beyond City buses: 1160 g-CO_2/km in 2020 & 810 g-CO_2/km in 2030 and beyond
CO_2 emissions reduction target	Up to 2030, the emission targets set under the Swiss CO_2 law (BAFU, 2020)
	By 2050, achieve a net-zero emission in energy system*
Fossil fuel prices	IEA's Sustainable Development Scenario prices (IEA, 2020)
Transport fuel tax	Current climate levy and fuel taxes are for diesel and gasoline. For new transport fuels (electricity/hydrogen), mineral oil tax equivalent to gasoline is applied

* Only from CO_2 emissions from fuel combustion and industrial processes. We exclude international aviation and agriculture. Between 2030 and 2050, the CO_2 cap is linearly applied.

We reiterate, STEM model use the car fleet and mobility demands from the BedDeM (Section 8.2). Thus, the personal mobility part of STEM is partly static and therefore the baseline and LC100 scenarios in Kannan et al. (2022) cannot be compared. Due to the introduction of the consumer segment and new BEV charging infrastructure details, the results are not compared with earlier studies. Most of the STEM model application are optimized with perfect foresight, whereas in this project, we apply myopic approach to facilitate co-simulation and because of the nature of the policies assessed with STEM.

8.2 Results

8.2.1 Fleet composition

The baseline, which required a few re-computations for plausibility and technical issues, is the following, as for the vehicle stock:

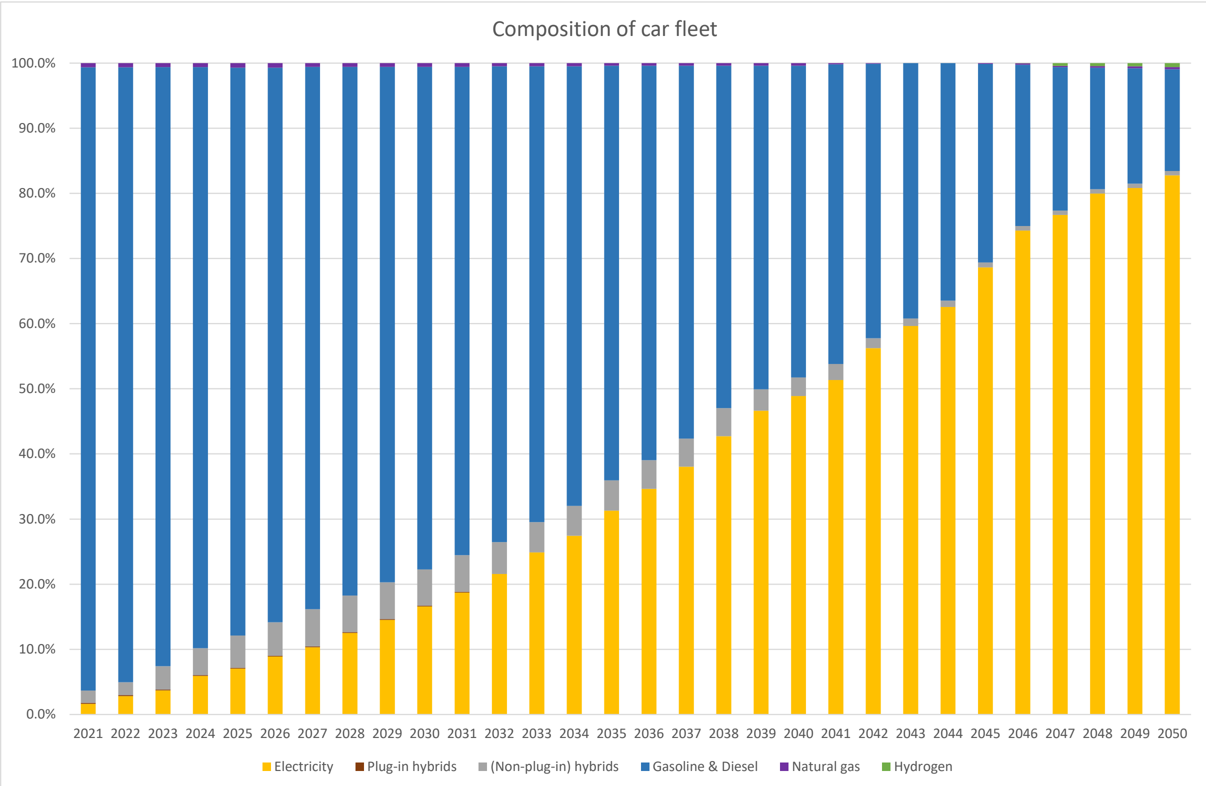

Figure 13: The fleet composition in the baseline

ICE progressively reduce their share in the stock, mainly crowded-out by battery electric vehicles and, for a transient period, by hybrids[33]. The share of battery electric cars in the Swiss car fleet is shown in Table 4[34]:

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040	2050
Share of BEV in the fleet	1.6%	2.8%	3.7%	5.9%	7.0%	8.9%	10.3%	12.5%	14.5%	16.6%	48.9%	82.8%

Table 4: Fleet composition in the baseline as for BEV share

[33] For a discussion of plug-in hybrids see the Section 10.3.
[34] The BedDeM model generate values for all individual years 2021-2050. Here, a selection of the years is presented.

In addition to its internal use, this baseline also can serve as reference point for a discussion of the consequences of such assumption vis-à-vis the system level optimization. With respect to the Energy Perspectives 2050+ ZERO BASIS scenario (ES+)[35], there is a perfect alignment with the total number of cars in 2050 (5’529’222 in the baseline and 5’213’309 in ES+).

The composition in 2050 in the baseline is more concentrated in only two technological families: 82.8% electric, 17.2% ICE driven with carbon-neutral liquid fuels. ES+ fleet in 2050 contains 68.3% battery electric, 14.6% fossil fuel, 9.7% hybrids, 7.5% hydrogen vehicles. There are two main differences. The baseline does not exhibit a permanent presence of hybrids[36] and does not exhibit a late take-off of hydrogen fuel cells vehicles.

With respect to SFOE “Scenario framework for electricity network planning”[37], issued on 23 Nov. 2022, this baseline generates 2’634’566 EVs in 2040, nicely between Scenario 2 (2’520’000), Scenario 1 (2’940’000) and Scenario 3 (3 230 000). For 2030, the PROBOUND baseline indicates 854’179 EV, which is slightly below all scenarios (870’000 in Scenario 3, 930’000 in Scenario 1 and 980’000 in Scenario 2). In the baseline, a value of 967’998 is achieved in 2031[38].

8.2.2 Sales

Consumers in the model took thousands of individual decisions, resulting in the following share of BEV in sales:

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040	2050
Share in sales of BEV	11.1%	16.3%	31.5%	35.2%	35.9%	31.9%	43.5%	38.1%	43.3%	42.5%	62.5%	97.9%

Table 5: Share of BEV on sales in the baseline

In terms of comparison with actual data of sales, the baseline (and all other scenarios, since they do not innovate until 2023 and they share with the baseline all the previous years) aligns quite well with real data (while remaining very slightly below)[39]: the baseline indicates for 2022 a percentage of 16.3%

[35] Source: Tabelle 02-01: Anzahl der Fahrzeuge in der Flotte nach Segment im Szenario ZERO Basis, Sheet «02 Flottenbestand», file: EP2050+_Detailergebnisse_2020-2050_Verkehrssektor_alle_Szenarien_2021-03-30.xlsx

[36] This is in line with the foreseen ban on hybrids proposed for the European market by the EU Commission. In the model, this development is endogenous and derives from the expected price dynamics and the evolution of the evaluation of hybrids in the media and public environment.

[37] https://www.bfe.admin.ch/bfe/en/home/supply/electricity-supply/electricity-networks/grid-development-electricity-grid-strategy/scenario-framework.html and in particular p. 5 of https://www.bfe.admin.ch/bfe/en/home/versorgung/stromversorgung/stromnetze/netzentwicklung-strategie-stromnetze/szenariorahmen.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZGUvcHVibGljYX/Rpb24vZG93bmxvYWQvMTA3NDk=.html

[38] The policy implication is that, while TSOs and DSOs may in principle consider the three scenarios as a high, a low, and an intermediate scenario, the baseline would suggest rather a rapid temporal sequence of earlier the lowest, then the intermediate, then the highest.

[39] Source: AutoSchweiz, 2nd Januar 2023.

of Battery electric vehicles in sales whereas AutoSchweiz data indicates 17.3%. For 2021, the respective values are 11.1% and 13.3%.
Year-by-year fluctuations in aggregate values of the baseline reflect all changes occurring in the year, notably the successive waves of heterogenous consumers deriving from partial participation to market.

8.2.3 Modal shares

In terms of billions of personal km by mode of transportation, the baseline scenario exhibits the following values:

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2040	2050
Cars	81.35	80.20	81.08	82.71	80.53	82.92	80.82	83.43	82.21	83.21	88.23	86.00
Public transport **(including trains)**	39.49	40.26	41.35	42.52	42.93	43.57	44.33	45.94	45.96	46.50	50.35	58.05
Trains	30.78	31.02	32.03	32.98	33.00	33.42	34.00	35.48	35.25	35.65	35.95	41.35
Soft mobility	16.58	16.56	16.33	16.61	16.67	16.64	17.28	16.99	17.42	17.22	15.50	17.03
Total	137.42	137.02	138.76	141.84	140.13	143.13	142.43	146.36	145.59	146.93	154.08	161.08

Table 6: Modal split in billions of personal km in the baseline

We calibrated with real data from FSO[40]. The calibration target for the mobility module is the pkm of private motorized road transport; rail and cable cars; public road transport; human-powered mobility in the year 2015. The objective function is to minimize the sum of the difference between the target and simulated yearly sum. The simulated yearly sum is calculated from the trip pkm (1 week of schedule) × 4 weeks × 12 months.
With respect with real values, as shown in the table below, the baseline fits the logical development as for the total pkm of a rising trend, of course it misses the massive drop in 2020 and 2021, caused by disruptions of the pandemic. Without having a too close correspondence, we consider it is a broadly acceptable approximation.

	Real values									
	Year of calibration									Computed in Baseline
	2015	2016	2017	2016	2017	2018	2019	2020		2021
private motorised road transport	97	99	101	99	101	102	103	85		81
rail and cable cars	21	21	21	21	21	21	22	14		17
public road transport	4	4	4	4	4	4	5	3		23
human-powered mobility	8	8	8	8	8	8	8	8		31
total	130	132	134	132	134	135	138	110		152

Table 7: Real data in billions of passenger km for 2015-2020 and the value of the baseline in 2021

Compared to the Base scenario of the Verkehrperspektiven 2050 (shown in the table[41] below) the Probound baseline exhibits larger grown in pkm. The models involved in the PROBOUND project, have been calibrated by historic data, not on particular projections. PROBOUND computes a rise of 15% in total person-km between 2026 and 2050, compared to the 7.3% of the Basis scenario.

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[40] https://www.bfs.admin.ch/bfs/en/home/statistics/mobility-transport/passenger-transport/performance.html - file: gr-e-11.04.01.01-je
[41] Source: p. 153, file “verkehrsperspektiven2050-schlussbericht.pdf”.

Attributing this difference would require a deep knowledge of the assumption and methods of both modelling exercises. For what matters in this document, the broad picture of a significant evolutionary rise is common.

Tabelle 9: Gesamtüberblick Ergebnisse - Szenario BASIS

BASIS	2017	2025	2030	2035	2040	2045	2050	Δ 2050-2017	2050-2017[%]
Verkehrsleistungen, Mrd. Personenkilometer									
PW	**91.0**	**94.1**	**96.2**	**96.2**	**96.2**	**95.2**	**93.6**	**2.6**	**2.9%**
konventionell	91.0	94.1	95.2	91.7	89.3	75.6	62.1	-28.9	-31.8%
automatisiert	-	0.0	1.0	3.4	5.9	18.3	30.3	30.3	
On-Demand	-	0.0	0.0	1.2	1.1	1.3	1.2	1.2	
ÖV	**26.0**	**26.8**	**28.1**	**30.2**	**31.3**	**32.4**	**33.7**	**7.7**	**29.4%**
Schiene	21.1	21.7	22.9	24.8	25.8	26.8	28.0	6.9	33.0%
Nahverkehr	5.0	5.1	5.2	5.4	5.5	5.6	5.7	0.7	14.3%
Velo	**2.7**	**3.0**	**3.4**	**3.8**	**4.2**	**4.7**	**5.3**	**2.6**	**97.2%**
Fuss	**4.9**	**5.2**	**5.4**	**5.6**	**5.7**	**5.8**	**5.9**	**1.0**	**21.1%**
Gesamt	**124.6**	**129.1**	**133.1**	**135.8**	**137.5**	**138.1**	**138.5**	**13.9**	**11.2%**
Modal Split, %									
PW	73.1%	72.9%	72.3%	70.9%	70.0%	68.9%	67.6%	-5.4%-P.	-7.5%
ÖV	20.9%	20.8%	21.1%	22.2%	22.8%	23.5%	24.3%	3.4%-P.	16.4%
Velo	2.1%	2.3%	2.5%	2.8%	3.1%	3.4%	3.8%	1.7%-P.	77.4%
Fuss	3.9%	4.0%	4.1%	4.1%	4.1%	4.2%	4.3%	0.3%-P.	8.9%

Table 8: Verkehrperspektiven 2050 – Basis Szenario – modal split and billions passenger km

8.2.4 Baseline results from STEM

In the following subsections, we describe selected parameters from the baseline results. We reiterate that the Baseline aims to reach a net-zero emission goal by 2050 across the entire Swiss energy system (without any sectoral emission reduction targets) and is not a business as usual scenario. It uses the car fleet and mobility demands from the baseline scenario of the BedDeM model (Table 6 & Figure 13).

8.2.4.1. Final energy and CO_2 emissions

In the baseline scenario, the final energy demand declines across the end use sector as the result of the assumed technology progress and policy measures (see Table 3). Figure 14 (left panel) shows the trend in the final energy demand (bars) and transport fuel demand (dashed line) in the Baseline scenario. Total final energy in the baseline scenario declines by 40% in 2050 compared to the 2020 level. The final energy is dominated by zero carbon energy carriers, like electricity, hydrogen, bio-, and synthetic fuels. Nevertheless, the energy system retains some fossil fuels and emissions from these fuels are offset by negative emission technologies (NET), like biomass with CCS. The right panel in Figure 14 shows the energy system wide CO_2 emissions. While the transport sector is fully decarbonized by 2050, some end use sectors emit CO_2 in 2050. Thus, NET are inevitable for achieving the net-zero goal cost-effectively.

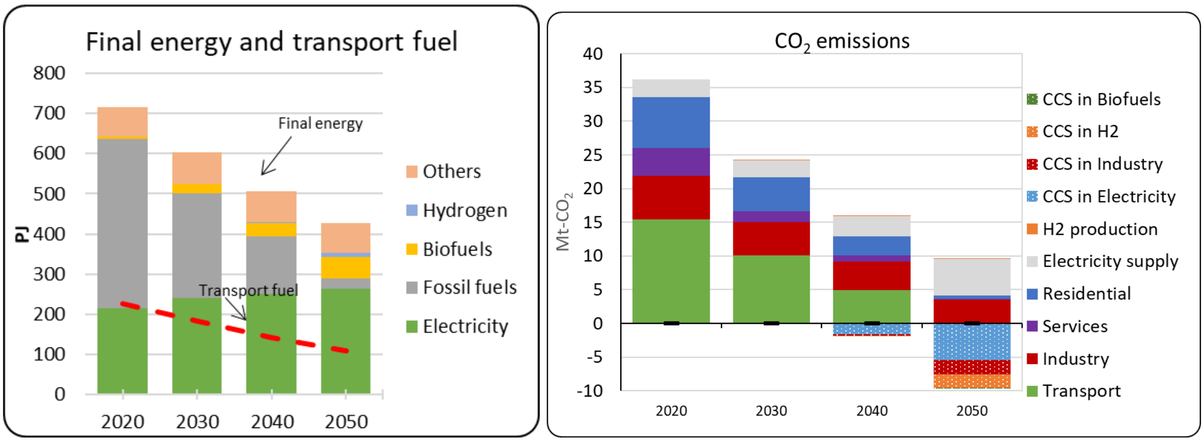

Figure 14: Total final energy demand, transport fuel demand and CO_2 emission trajectories[42].

A sheer share of the reduction in the final energy consumption concerns transport fuels, resulting in a decline of about 40%. The decline in the transport fuels is driven not only by fuel efficiency but also by switching to alternative fuels and drivetrains. The left panel in Figure 15 shows the transport sector energy consumption by fuels. A steady electrification across all transportation modes results in large reduction in fossil fuels. By far, the largest reduction in the consumption of transport fuels is realized in the car fleet.The electricity demand for public transport, including trains and the electrification of bus fleet, increases by 90% from the 2020 levels. As the stringency of the mitigation increases, zero carbon fuels such as hydrogen and biofuel play a stronger role. Zero-carbon fuels in end use sectors will fully substitute fossil fuels in transportation modes like trucks and buses in 2050 and the transport sector is fully decarbonized by 2050 (see Figure 14).

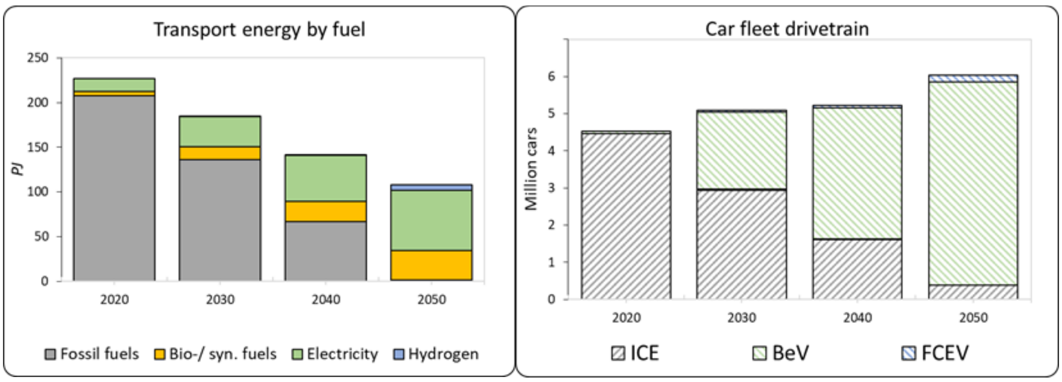

Figure 15: Transport sector fuel consumption and car fleet in baseline scenario

8.2.4.2. Electricity supply

Due to electrification of the end use sectors, future electricity demand increases (see Figure 14). The transport sector (all passenger and freight transportation mode) alone requires an additional electricity demand of about 14 TWh for the 'direct' electrification in 2050 compared to 2020 levels (see Figure

[42] The left panel shows the trajectories of the final energy demand and transport fuel demand (dashed lines) in the baseline scenario. Right panel elucidates CO_2 emission trajectories of the whole energy system.

16, left panel). Besides the direct electrification of the transport sector, the sector uses hydrogen and synthetic fuels, which are partly produced from electricity. Figure 16 shows the development of the Swiss electricity supply sector (left panel) and sources of hydrogen production (right panel). Besides phasing out of nuclear energy in 2050, about 23 TWh of new renewable electricity is produced in 2050, which requires both diurnal and seasonal storages. The total electricity demand in the end use sector is also plotted in Figure 16. The difference between the demand and total electricity supply are due to the other uses of electricity, e.g. hydrogen production. Hydrogen is partly used as seasonal storage to cope with the high share of renewable electricity. About 1.4 TWh hydrogen is shifted from summer to winter (1.2 TWh) and spring (0.2 TWh). Hydrogen is also produced from biomass with CCS (see Figure 16).

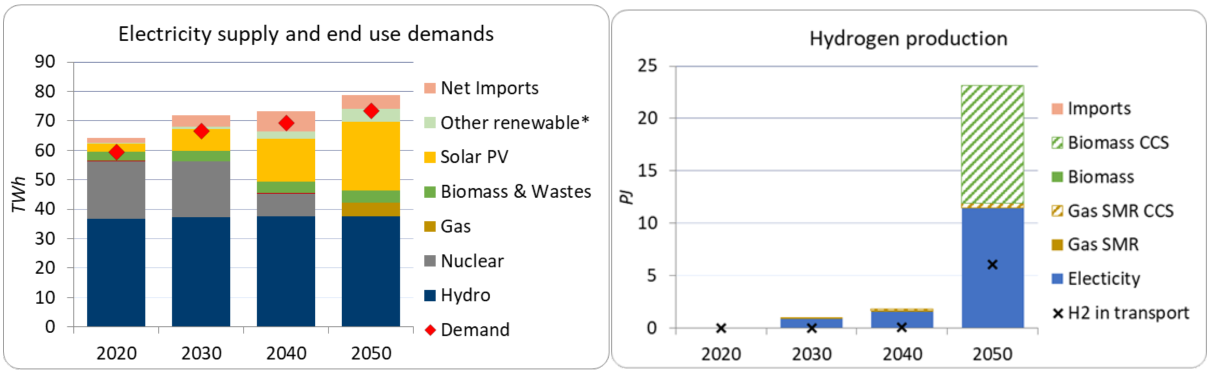

Figure 16: Electricity supply, demand and hydrogen production in baseline scenario[43].

To assess the impact of BR polices implemented in BedDeM, we compare the results with the baseline results. Whenever, we say, BR polices in STEM, we mean, use of car fleet and demand from BedDeM. Thus, the only change in STEM model is revised mobility demand and car fleet based on BR polices are implemented in BedDeM. The rest of the assumption remain unchanged.

[43] The left panel shows the electricity supply and demand in the baseline scenario. In the right panel, we show primary sources of hydrogen production in the baseline scenario.

9 The effects of 8 policies and 21 designs

9.1 The results in terms of fleet composition

The fleet turns out to be influenced by the policy designs, activated for three years (2023, 2024 and 2025) and implemented separately. In particular, the percentage of EVs in the total fleet is an important KPI for look at the policies effects. We show corresponding results in the following table.

		2023	2024	2025	2026	2027	2028	2029	2030	2040	2050
Baseline		3.7%	5.9%	7.0%	8.9%	10.3%	12.5%	14.5%	16.6%	48.9%	82.8%
Design	Short description[44]										
BUB1	Positive messages in neutral media	5,5%	8,4%	11,0%	14,4%	17,0%	20,6%	23,4%	26,3%	61,9%	88,4%
BUB2	Positive mess. In posit. Media	5,5%	8,4%	11,1%	14,4%	17,3%	20,8%	23,6%	26,5%	62,9%	88,6%
BUB3	Positive mess. In neg. media	5,4%	8,3%	11,0%	14,3%	16,8%	20,4%	23,2%	26,2%	63,0%	88,6%
BUB4	More exposure to posit. Media	5,3%	8,2%	11,0%	14,1%	17,0%	20,4%	23,3%	26,3%	63,0%	88,7%
SLOCH1	Charging opport. Tenants	4,9%	7,0%	8,5%	12,0%	14,5%	17,6%	20,6%	23,5%	59,0%	85,1%
SLOCH2	Charging opp. Work	4,6%	6,7%	8,1%	11,6%	14,3%	17,4%	20,5%	23,4%	59,0%	84,4%
SLOCH3	Charging opp. Shopping	4,7%	6,9%	8,6%	12,1%	14,7%	17,9%	21,0%	24,0%	60,1%	85,0%
SLOCH4	Charging opp. Homeowners	4,5%	6,7%	8,3%	11,9%	14,6%	17,6%	20,7%	23,8%	59,2%	84,8%
FACH1	Fast Charging fin. Supp.	5,5%	7,9%	10,3%	14,9%	18,9%	23,3%	27,8%	32,0%	74,0%	90,0%
FACH2	FC nat. stand.+fin. Supp.	5,8%	8,3%	10,7%	15,2%	19,4%	23,6%	28,3%	32,4%	74,0%	90,6%
VIS1	Visib. FC 2 km	5,4%	8,3%	11,0%	14,2%	16,8%	20,4%	23,3%	26,3%	62,4%	88,4%
VIS2	Visib FC 5 km	5,5%	8,4%	11,2%	14,4%	17,4%	21,0%	23,9%	27,0%	62,8%	88,3%
LAB1	Comm. Campaign label	5,2%	7,8%	10,2%	13,7%	16,5%	20,3%	23,2%	26,1%	62,0%	87,9%
LAB2	"A" only zero emissions	5,1%	7,7%	9,9%	13,0%	14,9%	17,7%	20,2%	22,7%	60,2%	87,0%
INDE1	Emission list at dealers	5,5%	8,5%	11,3%	14,8%	18,0%	21,6%	24,5%	27,5%	64,1%	88,8%
INDE2	Charging map at deal.	5,4%	8,4%	11,1%	14,3%	17,1%	20,7%	23,5%	26,5%	64,3%	89,3%
INDE3	Payment simplification at dealers	5,5%	8,5%	11,2%	14,5%	17,5%	21,2%	24,2%	27,3%	64,9%	89,8%
TT1	EV trials	5,9%	8,7%	11,4%	16,2%	20,5%	24,9%	29,8%	34,4%	77,6%	91,6%
TT2	Micro-mob. Trials	4,8%	6,9%	8,2%	11,7%	14,4%	17,5%	20,6%	23,5%	58,9%	84,6%
TT3	GA trials	4,1%	6,3%	7,5%	9,7%	11,2%	13,7%	15,6%	17,7%	54,7%	86,8%
TCO1	EV subsidy	6,6%	9,5%	12,4%	16,0%	18,8%	22,2%	25,0%	27,5%	58,5%	85,2%

Table 9: Fleet composition in terms of BEV shares

[44] For a longer description see Table 1 and Section 7.

The fleet exhibits a rising share of the BEV, with some policies leading to a share that is the double than the baseline in 2030.

In particular, it's useful to consider the year in which the fleet is at least 50% composed of battery electric vehicles, is an important aspect as it has an impact on the total emissions of the decades in front of us. The results of the different policies are shown in the following table.

		Year of EV majority in the fleet
Baseline		2041
Design	Policies	Year of EV majority in the fleet
BUB1	Positive messages in neutral media	2037
BUB2	Positive mess. In posit. Media	2037
BUB3	Positive mess. In neg. media	2037
BUB4	More exposure to posit. Media	2037
SLOCH1	Charging opport. Tenants	2038
SLOCH2	Charging opp. Work	2038
SLOCH3	Charging opp. Shopping	2037
SLOCH4	Charging opp. Homeowners	2038
FACH1	Fast Charging fin. Supp.	2035
FACH2	FC nat. stand.+fin. Supp.	2035
VIS1	Visib. FC 2 km	2038
VIS2	Visib FC 5 km	2038
LAB1	Comm. Campaign label	2037
LAB2	"A" only zero emissions	2038
INDE1	Emission list at dealers	2037
INDE2	Charging map at deal.	2037
INDE3	Payment simplification at dealers	2037
TT1	EV trials	2034
TT2	Micro-mob. Trials	2038
TT3	GA trials	2040
TCO1	EV subsidy	2038

Table 10: Year in which the majority of the car fleet is electric

Under all policies, sales of EV increases compared to the baseline scenario. However, the strength of the effects does vary among the different policies. Carbon neutrality is achieved when climate-neutral fuels are available and utilized by all the ICE vehicles remaining in the fleet.

9.2 The short term results in terms of sales

As decision-making is performed by individual agents, the policies can influence decisions, primarily on individual purchasing decisions. On the macro-level these decisions can be summarized in terms of the shares of electric vehicles in total sales and the deviation from the baseline (with a plus sign indicating that the values in the scenario implementing the designs are higher than the baseline, highlighted by bold characters, and the opposite indicated by a red color).

		BEV share in the sales					
		2023		2023-2025		2023-2027	
Baseline		31.5%		34%		36%	
Design	Short description[45]	First year of introduction		First 3 years		First five years	
		Share in the sales	Deviation from the baseline	Share in the sales	Deviation from the baseline	Share in the sales	Deviation from the baseline
BUB1	Positive messages in neutral media	46.6%	**(+15.1%)**	45.0%	**(+10.7%)**	45.7%	**(+10.0%)**
BUB2	Positive mess. In posit. Media	45.7%	**(+14.2%)**	45.1%	**(+10.8%)**	46.3%	**(+10.6%)**
BUB3	Positive mess. In neg. media	46.0%	**(+14.5%)**	45.0%	**(+10.7%)**	45.2%	**(+9.5%)**
BUB4	More exposure to posit. Media	46.0%	**(+14.4%)**	44.5%	**(+10.2%)**	45.6%	**(+9.9%)**
SLOCH1	Charging opport. Tenants	33.6%	**(+2.1%)**	36.3%	**(+2.0%)**	38.9%	**(+3.2%)**
SLOCH2	Charging opp. Work	34.0%	**(+2.5%)**	35.6%	**(+1.4%)**	39.0%	**(+3.3%)**
SLOCH3	Charging opp. Shopping	34.0%	**(+2.5%)**	37.3%	**(+3.0%)**	39.9%	**(+4.2%)**
SLOCH4	Charging opp. Homeowners	34.3%	**(+2.7%)**	37.3%	**(+3.0%)**	39.7%	**(+4.0%)**
FACH1	Fast Charging fin. Supp.	39.3%	**(+7.8%)**	47.9%	**(+13.6%)**	53.7%	**(+18.0%)**
FACH2	FC nat. stand.+fin. Supp.	33.6%	**(+2.1%)**	36.3%	**(+2.0%)**	38.9%	**(+3.2%)**
VIS1	Visib. FC 2 km	46.3%	**(+14.8%)**	44.6%	**(+10.3%)**	45.1%	**(+9.4%)**
VIS2	Visib FC 5 km	46.0%	**(+14.5%)**	45.2%	**(+10.9%)**	46.8%	**(+11.1%)**
LAB1	Comm. Campaign label	41.5%	**(+10.0%)**	43.3%	**(+9.0%)**	45.7%	**(+10.0%)**
LAB2	"A" only zero emissions	42.2%	**(+10.6%)**	40.4%	**(+6.1%)**	38.3%	**(+2.6%)**
INDE1	Emission list at dealers	47.2%	**(+15.6%)**	46.9%	**(+12.6%)**	48.2%	**(+12.5%)**
INDE2	Charging map at deal.	47.0%	**(+15.5%)**	45.0%	**(+10.7%)**	46.1%	**(+10.4%)**
INDE3	Payment simplification at deal.	47.2%	**(+15.6%)**	45.6%	**(+11.3%)**	47.3%	**(+11.6%)**
TT1	EV trials	44.3%	**(+12.8%)**	52.5%	**(+18.2%)**	57.8%	**(+22.1%)**
TT2	Micro-mob. Trials	33.5%	**(+1.9%)**	35.1%	(+0.9%)	38.6%	**(+2.9%)**
TT3	GA trials	35.4%	**(+3.8%)**	28.4%	**(-5.8%)**	29.2%	(-6.5%)
TCO1	EV subsidy	46.6%	**(+15.0%)**	48.5%	**(+14.2%)**	47.8%	**(+12.1%)**

Table 11: Effects of policies in the short run

[45] For a longer description see Table 1 and Section 7.

While most often effects can be seen in the time while the policies are enacted, we also see *fading-out* effects, as decisions from agents can be influenced by previous decisions of other agents (via the reference to other agents). The effects ranges from a +1.9% to +15.6% depending on the design. There is a certain polarization (with 7 designs with a relatively weak impact and 13 with an impact of 10% or more, only one design is in intermediate position). Given that we used a model-based approach, and the underlying models are simplifications of reality, therefore results need to be treated with care. Depending on the specific policy one of the following patterns can be observed in its short-term effects.

- Taming (with some reduction in the percentage of increase): 10 cases
- Fading out (with a deep reduction to relatively low levels): 1 case
- Acceleration and growing impact: 5 cases
- Relatively stable level: 4 cases
- A reversal in the negative territory: 1 case

It can also be underlined that the policies providing price signals are effective in modifying purchases and behaviors. Non-price policies are also effective. The effectiveness of the two types of policies is in the same order of magnitude.

The parametrization of a policy turned out as important as the type of policy itself. The ranking of policy effectiveness in the first three years, for instance, exhibit systematic "alternation" of designs deriving from different policies, as indicated in the following Table 12.

Design	BEV share in sales (2023-2027) ranked from highest to lowest
TT1	57.8%
FACH1	53.7%
INDE1	48.2%
TCO1	47.8%
INDE3	47.3%
VIS2	46.8%
BUB2	46.3%
INDE2	46.1%
BUB1	45.7%
LAB1	45.7%
BUB4	45.6%
BUB3	45.2%
VIS1	45.1%
SLOCH3	39.9%
SLOCH4	39.7%
SLOCH2	39.0%
SLOCH1	38.9%
FACH2	38.9%
TT2	38.6%
LAB2	38.3%
TT3	29.2%
Baseline	36.0%

Table 12: Share of battery electric vehicles in sales depending on policy design (short term)

These results can have far-reaching and diversified implications. For instance, media reception of a novel technology does have an impact of its adoption. This result, which stands in contrast to neoclassical economics, is rather in line with the science and practice of marketing, which demonstrate that consumers can be persuaded by the public conversation (including paid advertising). The focus of marketing science on business success is, however, preventing it to draw national-level implications (e.g. on total emissions). PROBOUND, by contrast, is obtaining such results, as it will be more clear in the following sections. This can be considered an innovative contribution of the project in the academic debate.

9.3 The results in the long term

The models generate yearly value for all variables. In what follows, the average of five years, centered in milestone years (2030, 2040) is taken, to smooth out yearly ups and downs. For the same aim, the average of three years is taken for 2050.

		BEV share in the sales					
		2030[46]		2040[47]		2050[48]	
Baseline		45.0%		77.9%		98.4%	
Design	Short description[49]	Share in the sales	Deviation from the baseline	Share in the sales	Deviation from the baseline	Share in the sales	Deviation from the baseline
BUB1	Positive messages in neutral media	49.4%	**(4.4%)**	80.7%	**(2.8%)**	99.6%	**(1.2%)**
BUB2	Positive mess. In posit. Media	49.8%	**(4.9%)**	81.4%	**(3.6%)**	99.7%	**(1.2%)**
BUB3	Positive mess. In neg. media	50.0%	**(5.1%)**	80.9%	**(3.1%)**	99.7%	**(1.2%)**
BUB4	More exposure to posit. Media	50.2%	**(5.3%)**	81.8%	**(4.0%)**	99.7%	**(1.2%)**
SLOCH1	Charging opport. Tenants	48.5%	**(3.5%)**	76.9%	(-1.0%)	98.8%	**(0.3%)**
SLOCH2	Charging opp. Work	49.2%	**(4.2%)**	77.3%	(-0.5%)	98.3%	(-0.1%)
SLOCH3	Charging opp. Shopping	50.1%	**(5.1%)**	78.2%	**(0.3%)**	98.7%	**(0.3%)**
SLOCH4	Charging opp. Homeowners	49.1%	**(4.2%)**	77.2%	(-0.6%)	98.5%	**(0.1%)**
FACH1	Fast Charging fin. Supp.	67.4%	**(22.4%)**	87.0%	**(9.1%)**	99.4%	**(1.0%)**
FACH2	FC nat. stand.+fin. Supp.	67.3%	**(22.3%)**	86.1%	**(8.2%)**	99.4%	**(1.0%)**
VIS1	Visib. FC 2 km	50.3%	**(5.3%)**	81.2%	**(3.3%)**	99.7%	**(1.2%)**
VIS2	Visib FC 5 km	50.4%	**(5.4%)**	81.4%	**(3.5%)**	99.6%	**(1.2%)**
LAB1	Comm. Campaign label	49.5%	**(4.5%)**	79.6%	**(1.7%)**	99.6%	**(1.2%)**
LAB2	"A" only zero emissions	44.5%	(-0.5%)	81.2%	**(3.4%)**	99.1%	**(0.7%)**
INDE1	Emission list at dealers	51.5%	**(6.5%)**	81.3%	**(3.4%)**	99.7%	**(1.2%)**

[46] Average 2028-2032.
[47] Average 2038-2042.
[48] Average 2048-2050.
[49] For a longer description see Table 1 and Section 7. Bold characters indicate positive differece, while the opposite indicated by a red color.

INDE2	Charging map at deal.	50.7%	**(5.8%)**	82.1%	**(4.2%)**	99.7%	**(1.2%)**
INDE3	Payment simplification at deal.	51.6%	(6.7%)	82.8%	**(4.9%)**	99.7%	**(1.3%)**
TT1	EV trials	71.0%	(26.1%)	89.2%	**(11.3%)**	99.6%	**(1.1%)**
TT2	Micro-mob. Trials	49.2%	(4.2%)	76.3%	(-1.6%)	98.0%	(-0.4%)
TT3	GA trials	36.9%	(-8.0%)	81.5%	**(3.6%)**	98.2%	(-0.2%)
TCO1	EV subsidy	47.2%	(2.3%)	79.3%	**(1.4%)**	96.3%	**(-2.2%)**

Table 13: Share of BEV in the sales (long term) depending on the policy design

The largest effects are for 2030, whereas for much later year, the saturation of the market and the lack of supply of ICE models in the ‘40s make the policies (applied in 2023, 2024 and 2025) substantially irrelevant (in sales, not in the stock). Actually, after 2025 there would be room for application (maybe of different) policies (e.g. different design in sequence). Albeit technically feasible, the time framework of the project did not allow the computation of such scenarios.

9.4 The effects on public transport

The effects of all policy designs on passenger km in public transport are included in the following Figure 17:

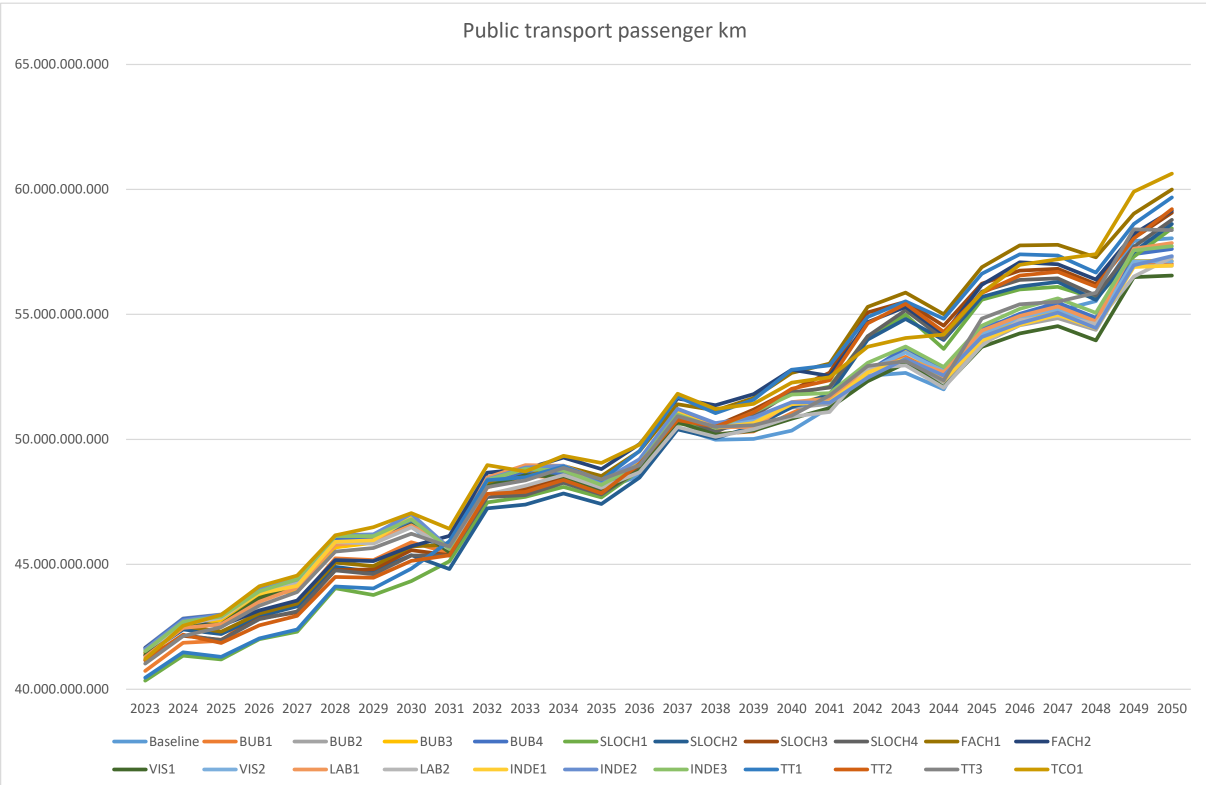

Figure 17: Public transport use depending on the policy design

With many designs, public transport is more used than in the baseline, mostly as an effect of BEV diffusion and the preference for longer distance of trains over electric vehicles. In particular, the designs that most increase the (positive) difference between 2050 and 2023 in the passenger km made in public transport are TCO1, BUB3, INDE2. Please note, however, that the difference is not large and also other policy design would have positive effects. For a more analytical picture of the impact of the policy design, the following Table 14 indicate the part of public transport in total passenger km, demonstrating that, albeit modestly, the policies increase the share of public transport, without any substitution by e.g. electric vehicles.

		Public transport share in the total passenger km					
		2030		2040		2050	
Baseline		31,6%		32,7%		36,0%	
Design	Short description[50]	Share	Deviation from the baseline	Share	Deviation from the baseline	Share	Deviation from the baseline
BUB1	Positive messages in neutral media	31,8%	**0,2%**	33,3%	**0,6%**	35,1%	-0,9%
BUB2	Positive mess. In posit. Media	31,8%	**0,2%**	33,3%	**0,6%**	35,1%	-0,9%
BUB3	Positive mess. In neg. media	31,8%	**0,1%**	33,4%	**0,7%**	35,2%	-0,8%
BUB4	More exposure to posit. Media	31,7%	**0,1%**	33,2%	**0,5%**	35,7%	-0,4%
SLOCH1	Charging opport. Tenants	29,7%	-1,9%	33,9%	**1,2%**	36,3%	**0,3%**
SLOCH2	Charging opp. Work	30,6%	-1,0%	33,5%	**0,8%**	36,3%	**0,3%**
SLOCH3	Charging opp. Shopping	30,8%	-0,9%	34,0%	**1,3%**	36,7%	**0,6%**
SLOCH4	Charging opp. Homeowners	30,5%	-1,1%	34,0%	**1,3%**	36,6%	**0,5%**
FACH1	Fast Charging fin. Supp.	30,9%	-0,8%	34,7%	**2,0%**	37,5%	**1,4%**
FACH2	FC nat. stand.+fin. Supp.	30,9%	-0,8%	34,7%	**2,0%**	36,9%	**0,9%**
VIS1	Visib. FC 2 km	31,6%	0,0%	32,9%	**0,2%**	34,7%	-1,3%
VIS2	Visib FC 5 km	31,9%	**0,3%**	33,4%	**0,7%**	35,2%	-0,8%
LAB1	Comm. Campaign label	31,6%	0,0%	33,5%	**0,8%**	35,9%	-0,1%
LAB2	"A" only zero emissions	31,5%	-0,2%	33,0%	**0,4%**	35,4%	-0,7%
INDE1	Emission list at dealers	31,8%	**0,2%**	33,3%	**0,6%**	35,0%	-1,0%
INDE2	Charging map at deal.	32,0%	**0,3%**	33,4%	**0,7%**	35,4%	-0,6%
INDE3	Payment simplification at deal.	31,7%	**0,1%**	33,7%	**1,0%**	35,6%	-0,4%
TT1	EV trials	30,1%	-1,5%	34,8%	**2,1%**	37,2%	**1,2%**
TT2	Micro-mob. Trials	30,4%	-1,3%	34,1%	**1,4%**	36,7%	**0,7%**
TT3	GA trials	31,4%	-0,3%	33,2%	**0,5%**	36,2%	**0,2%**
TCO1	EV subsidy	32,0%	**0,3%**	34,1%	**1,5%**	37,8%	**1,7%**

Table 14: Modal share of public transport on total passenger km

The baseline exhibits significant increase of the public transport from 29.8% (2023) and 31.6% (2030) to 36% (2050). Modest deviation are generated by the policies (in a range between -1.5% to 2%).

[50] For a longer description see Table 1 and Section 7. Bold characters indicate positive differece, while the opposite indicated by a red color.

Some policy design (SLOCH, FACH, TT and LAB2) reduce in 2030 the increase of share of public transport, but this is transitory, with none negatively impacting 2040. In 2050, some reductions in share (with respect to the significant increase of the baseline) are due to (all designs) of FACH, VIS, LAB and INDE. Since what matters for infrastructure planning is rather the total number of passenger km, these effects are not particularly significative.

9.5 Impact of BR polices in Swiss energy system

In the following subsections, we highlight impact of BR policies implemented in STEM. As such, the BR polices are not directly implemented in STEM. Instead, effective mobility demands and car fleets from the BR policies are used as input to STEM. Thus, compared to the baseline scenario, the change in STEM model are transport demand per modes and car fleet mix, which are based on BedDeM's BR polices (see Section 7) and their effects in BedDeM (Section 9.1-9.4). Before we describe the energy systemic impact of BR polices, we recap trend in STEM inputs relative to the Baseline.

Figure 18 (upper panel) shows the share of BEV driven pkm versus share of car-based mobility in total mobility. From 2030 to 2050, the share of car-based mobility decline from 60% to 56% while the share of public transport increases (see Figure 18 (lower panel)). In the short term (2030), the share of BEV in total car fleet increases up to 40% versus <20% in the baseline scenario. By 2050, share of BEV saturates between 85% and 92% (vs. 80% in baseline scenario) because all new cars enter in to the fleet are pure BEV (as ICE cars are not supplied by manufacturers after 2040 – see baseline assumptions in BedDeM in Section 8.1.2-8.1.2.5).

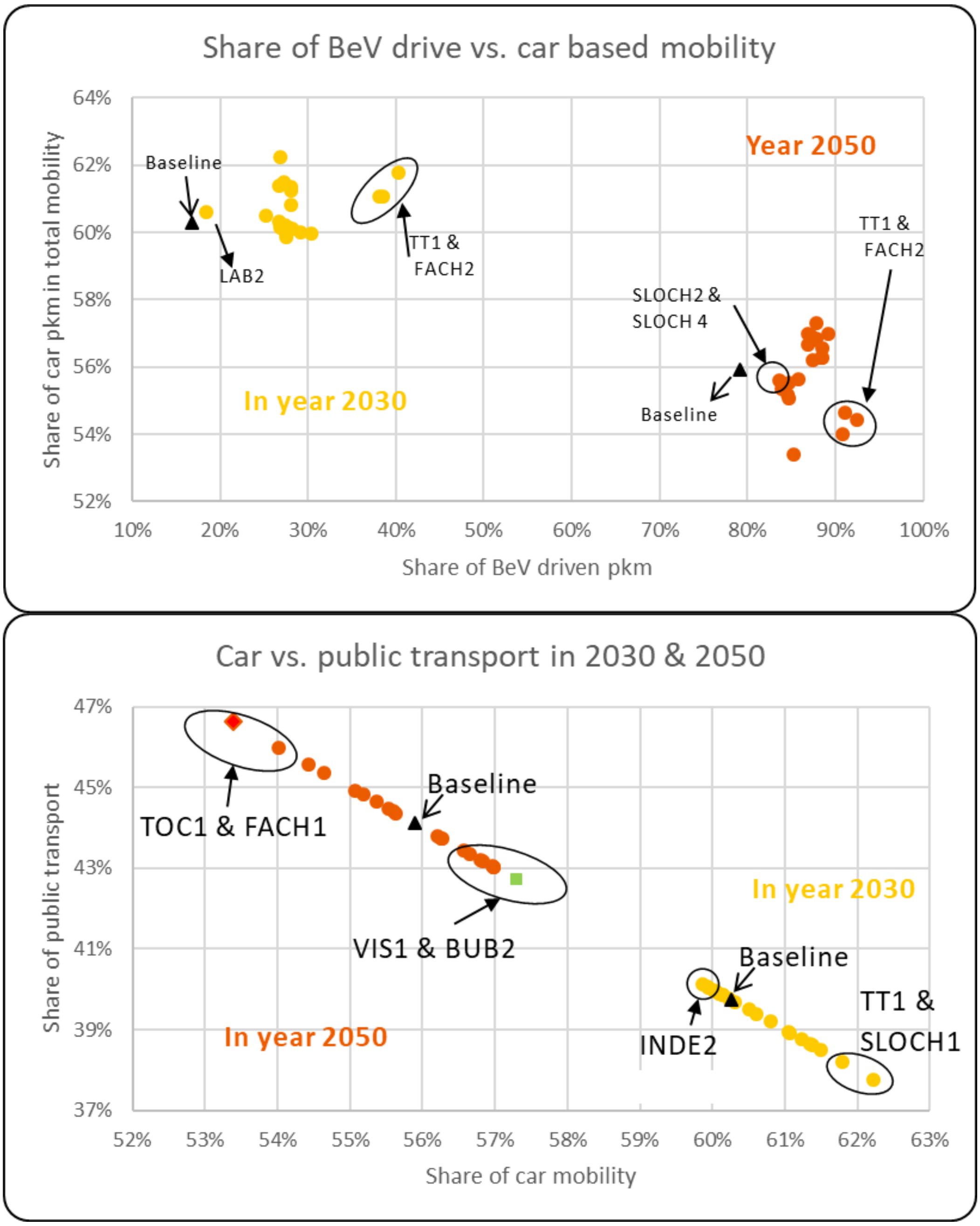

Figure 18: Trend in share of BEV driven car (in pkm) versus share of car based mobility (pkm) in total mobility demand (upper panel)[51].

The lower panel of Figure 18 shows the share of public transport with respect to car-based mobility in years 2030 and 2050. In the baseline, the share of public transport increase from 40% in 2030 to 44% in 2050 (black triangular markers). In year 2050, in the BR policies on visibility of fast charging station

[51] The lower panel elucidates the share of public transport with respect to car-based mobility across different BR polices in 2030 and 2050.

(VIS1) and positive media (BUB2), the share of car-based mobility increases to 57.5% vs. 56% in the baseline. This trend infers that the VIS and BUB polices have not only induced a high share of BEV, but consumers might perceive BEV as environmentally friendly and thereby use more cars (i.e. avoidance of public transport). By contrast, in the BEV subsidy (TOC1) and financial support to fast charging (FACH1) policies, the share of public transport increases compared to the baseline scenario. In other words, share of public transport increase to 47% while the share car-based mobility decline to 53% (vs. 56% in Baseline).

We present the selected energy system indicators with respect to change in BEV, which is an input parameter from BedDeM. Since BEV penetration are prominent in the short term, in Figure 19 (upper panel), we show the cumulative CO_2 emission from the transportation sector during 2024-2036. Obviously, a high penetration of BEV reduces CO_2 emissions. Particularly, the BR polices on EV drive trials (TT1) and financial support for charging station (FACH2) induce the highest CO_2 mitigation. In these policies, on an average, annually about one million tons of CO_2 is reduced compared to the Baseline scenario when the share of BEV in 2030 increase to 40% compared to 17% in the Baseline. The CO_2 mitigation from these BR polices helps avoiding expensive mitigation measures in other end use sectors. For example, expensive energy conservation measures in the industrial and residential sectors are avoided (see Figure 24). Therefore, CO_2 emissions in these sectors increase in 2030 (see Figure 20)[52] and costs are saved in such sectors. It is worth noting that using a pure cost optimization model, it is not possible to assess the tradeoff between CO_2 mitigation from building insulation versus BEV. This requires further research on BR in household decision-making, e.g. spending on home insulation (renovation) versus purchasing BEV. Once the building energy conservation measures are missed at the renovation cycle, it will be a missed opportunities as building renovation is cyclic. Thus, it can incur higher cost at the later years.

The short-term trends on CO_2 reduction continues in the long term (Figure 19 lower panel): the early uptake of BEVs induce an average yearly reduction of about 0.5 million CO_2 in the long term. Conversely, the impact of BR polices are negligible on sales. The CO_2 reductions seen in periods during 2037-2050 (Figure 19 lower panel) is mainly from the early stock turnover of ICE cars in the short term.

[52] As a cost optimization model, the system does not overshoot the 2030 CO_2 target. Therefore, it avoids investment in conservation measures, which were cost effective in the baseline.

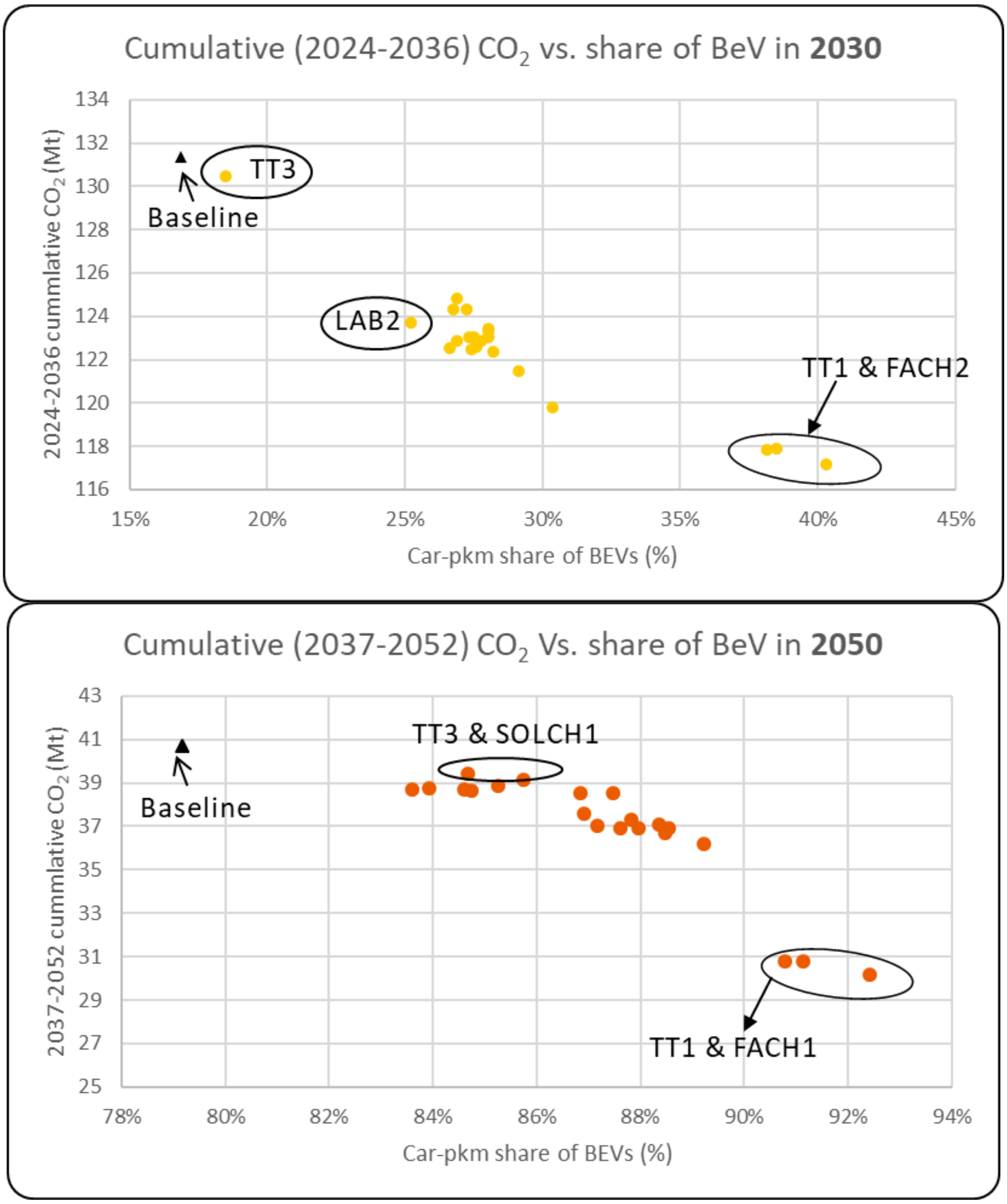

Figure 19: BEV penetration versus cumulative (2024-2036) CO_2 emission (left panel) and annual CO_2 emission in 2030 by sector (right panel)

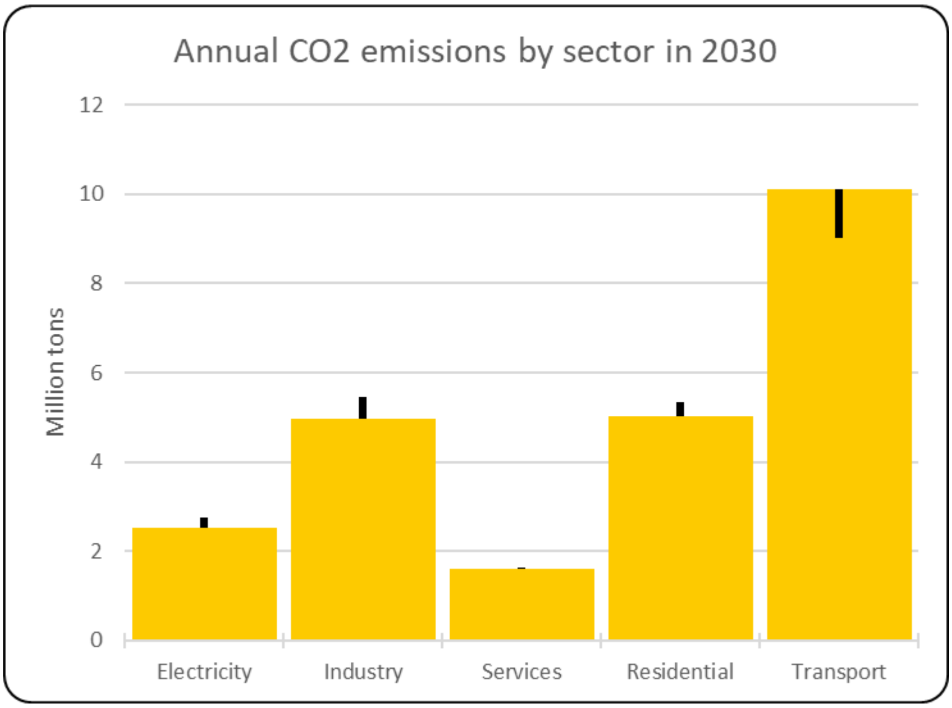

Figure 20: Annual CO_2 emission in 2030 by end use sector[53].

In terms of cost, there is no significant impact on the energy system cost in year 2050 as the share of BEV saturates in the long-term (92-95% BEV across the BR policies). However, the energy system cost is high in the short term (2030) due to the high share of BEVs in relation to the Baseline scenario. Policies that yield high CO_2 reduction (TT1 and FACH1) incur additional energy system cost of about CHF 2 billion in 2030 (upper panel in Figure 21). When we calculate the average CO_2 abatement cost from the total CO_2 reduction in the transport sector and total additional energy system costs, it is about 2000 CHF/t-CO_2[54]. Thus, BEV induced CO_2 mitigation cost is 2-4 times higher than the energy system wide mitigation in the baseline scenario of about 430 – 640 CHF/t-CO_2 in 2030 (see Figure 22). The high CO_2 mitigation cost (compared to the Baseline scenario) can be attributed to the purchase of BEV in early decades (as the car fleet is exogenously fixed in STEM) and their corresponding infrastructure (e.g. charging station, electricity). From Figure 24, it can be inferred that most of the additional energy system cost incurs in the end use sector, particularly in the transportation sector (including consumers willingly choose to incur such costs). It is important to assert that the high costs of FACH policies in STEM is due to the purchase of BEV in the early years (see car cost in Table 13 and the rapid fall in prices of BEV) and investments in respective BEV charging stations. However, the explicit costs of BR policies from the BedDeM model are not implemented in STEM. Based on the total CO_2 emission reduction in 2030 and additional cost of the energy system, we calculated the average CO_2 abatement

[53] The solid bars in yellow show the CO_2 emission level in the baseline scenario and the error bars in black indicate the changes in emission (wrt the baseline) across all BR policy scenarios. Pre-COVID real emissions of transport sector were 15 mln tonnes of CO_2-equivalent in 2019, so already the baseline does involve quite a significant fall. Source of the data: https://www.bafu.admin.ch/bafu/de/home/themen/klima/zustand/daten/co2-statistik.html, filename: CO2-Statistik-2022-07_DE.xlsx.

[54] This value does not consider the co-benefits in terms of air quality and noise.

cost. Majority of the BR policies have the CO_2 reduction potential of about 0.5 Mt-CO_2 and their CO_2 abatement costs are estimated to be 800 – 1400 CHF/t-CO_2 (see Figure 23). It is worth noting that the 21 BR policies are implemented independently. Therefore, emission reduction potential in Figure 23 in principle might be accumulated (but to ascertain this, a specific simulation should be run) and they must be treated as effect of individual BR policies.

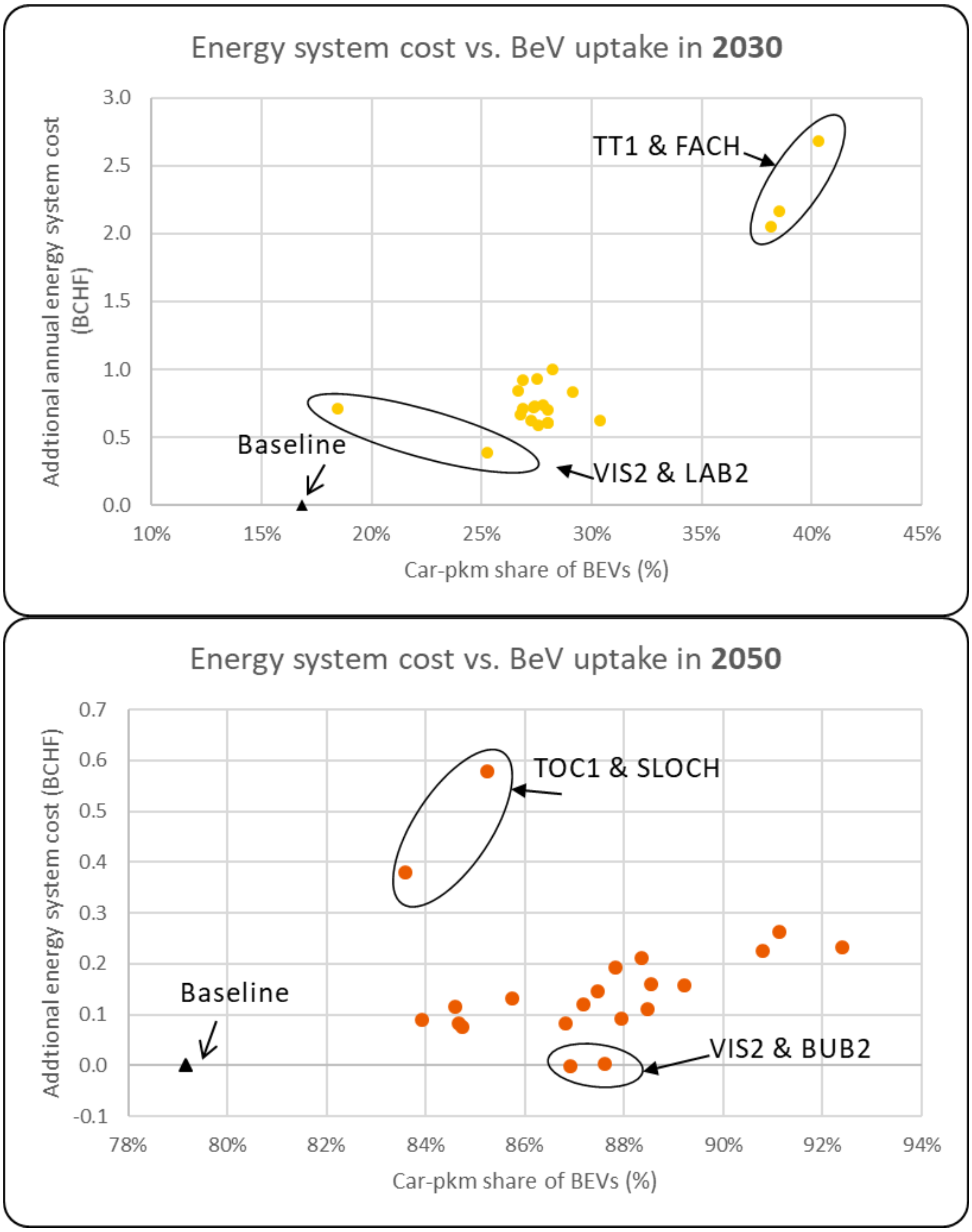

Figure 21: BEV penetration versus cumulative energy system cost in 2050 and 2050.

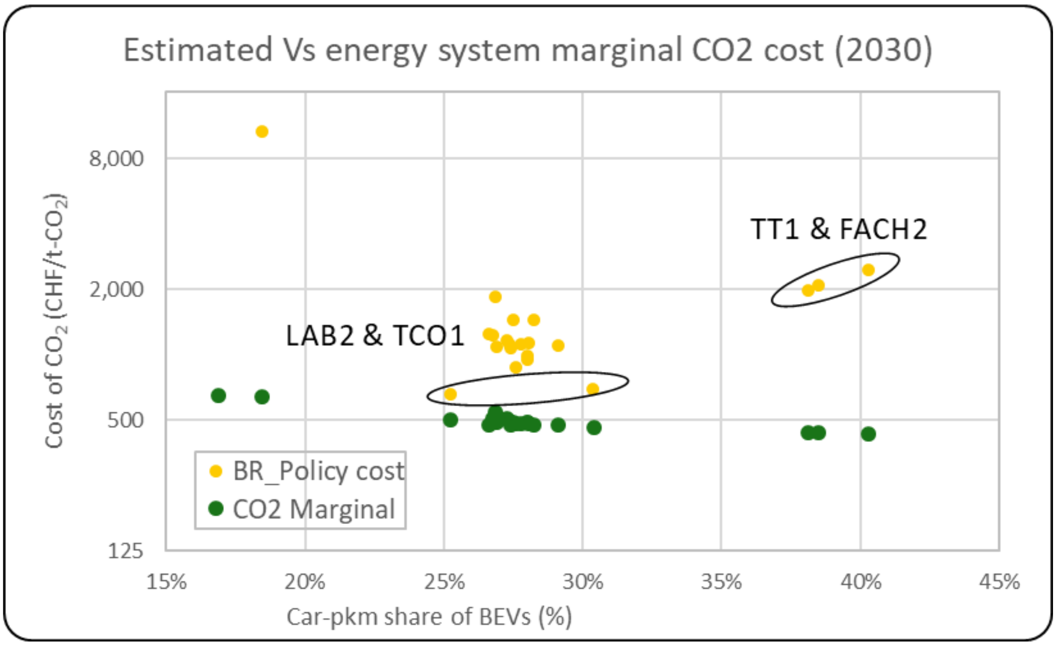

Figure 22: Estimated average CO_2 abatement cost in the transport sector due to BR policies versus energy system wide marginal cost of CO_2

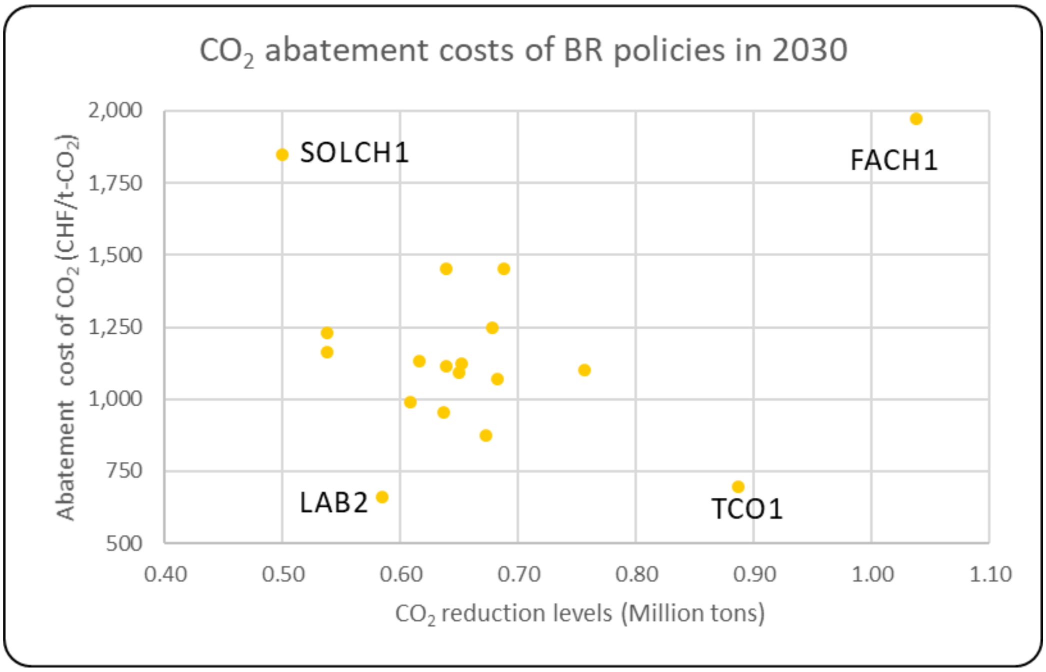

Figure 23: Calculated CO_2 abatement cost of PR policies based on the total energy system cost

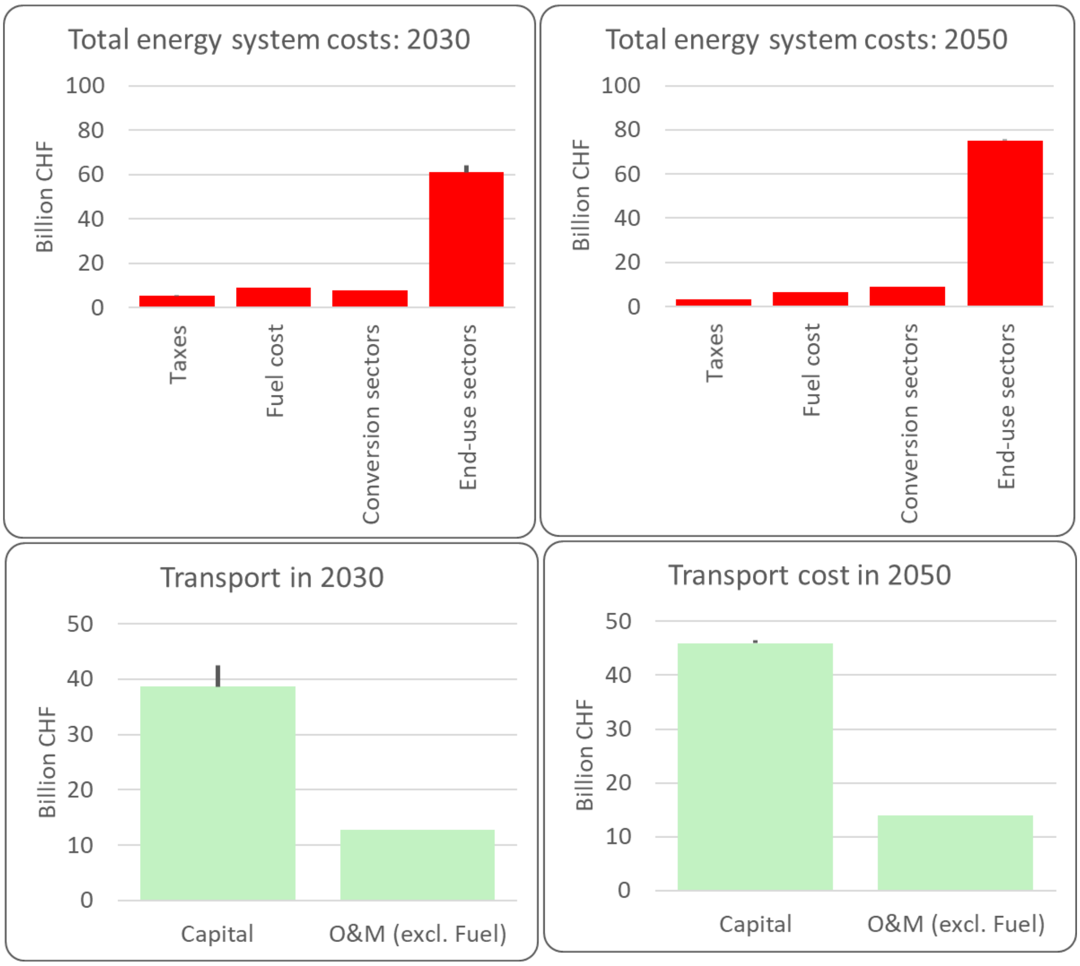

Figure 24: Change in undiscounted annual energy system cost in year 2030 and 2050 by sub-sector[55]. Change in transport sector capital and O&M costs, excluding fuel cost[56].

Electricity demand in the transport sector increases in line with the penetration level of BEVs and public transport demand, mostly trains. Figure 25 (lower panel) shows the change in electricity demand (in total and within the transport sector) across the BR policies in 2030 (solid bars refers to the baseline scenario). The incremental electricity demand is supplied through investments in solar PV and imported electricity, as illustrated in Figure 25 (upper panel). Due to the increased electricity demand, and share of new renewables, additional storage capacity is needed to cope with diurnal and seasonal variability. In this context, hydrogen plays a pivotal role as a storage energy carrier. Further, the hydrogen is also used for synthetic fuel (Synful) production (e.g., for trucks) and industries (for heating) (see Figure 25 – lower panel).

55 Upper panels.
56 The bar indicates the baseline cost and error bar show the changes from the baseline induced by the policies.

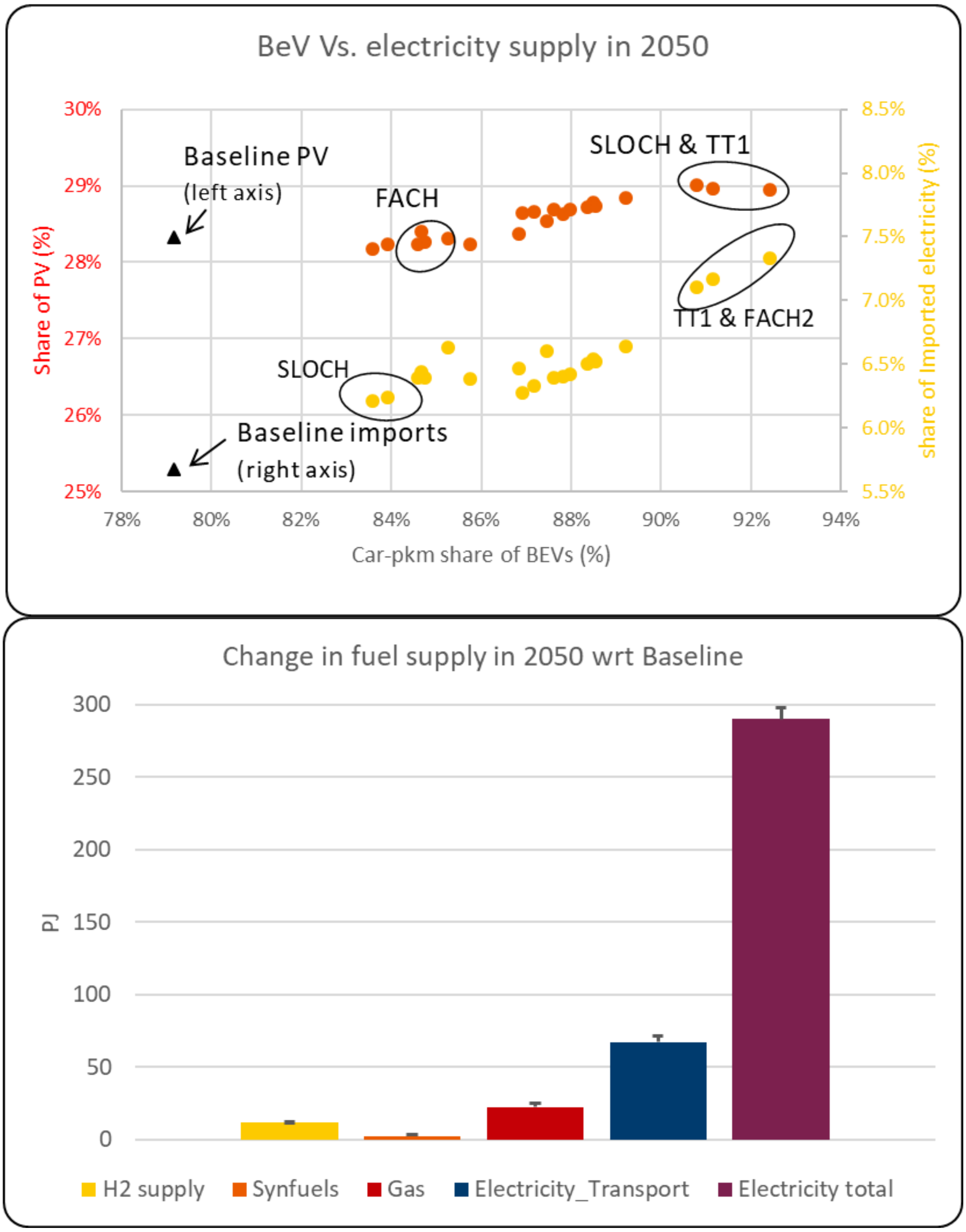

Figure 25: Share of imported electricity and solar PV supply in all BR policies[57]. Lower panel: change in selected fuels across all the BR policies in year 2050 with respect to the baseline[58].

[57] Upper panel, left vertical axis and right vertical axis, respectively.
[58] Bar plot.

9.5.1 Summary of BR policies' energy systemic impacts

In the short-term, BEV uptake reduces CO_2 emissions and the highest CO_2 emission reductions are achieved by EV trials (TT1) and financial support for charging station to fulfill national standards (FACH2). All the BR policies incur additional energy system costs, but reduce the need for mitigation measures in other sectors to meet the 2030 CO_2 reduction target. CO_2 mitigation from the BR polices avoids the most expensive energy conservation measures in the end use sectors.
The long-term impacts of BR policies are subtle due to BEV saturation as consumers do not have other car purchase option because sales of ICE cars are assumed not to be offered since 2040.

Additional electricity demands are often supplied by solar PV and electricity imports. Efficient integration of solar PV calls for more H_2 storage. Some end-use sectors use hydrogen/syngas instead of direct electrification, e.g. remaining ICE cars in 2050 use zero-carbon fuels; industry uses synthetic gas. Despite high effectiveness of BR polices in CO_2 mitigation, they incur high cost in long term too because, when building energy conservation measures are missed at the renovation cycle, it will be a missed opportunity. Then the energy system seeks alternatives, through expensive mitigation measure to meet the long-term goal.

9.6 Role of BEV charging infrastructure

In addition to the co-simulation of STEM and BedDeM model in assessing the impact of BR policies described section 9.5, we use standalone[59] STEM model for assessing the role of charging infrastructure and deployment of BEV, given their possible systemic importance. We explored different BEV charging infrastructure and their effects on the BEV deployment. We explored different BEV charging infrastructure and their effects on the BEV deployment. The provision of overnight charging (PRIV and RESID)[60] is most conducive for integrating BEVs into the energy system due to long parking durations that allow avoiding electricity demand peaks by utilizing controlled charging. When increased overnight charging is achieved by making PRIV chargers available to tenants, 2.82 million BEVs and 0.98 million PHEVs, and 1.5 million overnight chargers (1.4 million PRIV and 101 thousand RESID) are deployed. When more overnight charging is achieved through high RESID accessibility, 2.56 million BEVs and 1.01 million PHEVs enter the fleet, requiring 1.1 million PRIV and 139 thousand RESID overnight chargers. Adjusting building- or urban planning regulations could help achieve this. Further, we found that CI with lower rated power is sufficient and more cost-effective for overnight/home charging.

Table 15 and Table 16 show selected indicators on charging stations.

Public charging (PC) options away from home (COMM and RAPID) support the BEV rollout by making their adoption cost-effective for consumers who cover long-distance trips or cannot charge (overnight) at home. Charging infrastructure (CI) with higher rated power is cost-advantageous for this, as faster charging throughout the day allows more efficient use of renewable energy from photovoltaics. The

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[59] It is worth noting that for this analysis, the car purchase decision is also made in STEM, unlike in the BR policy impact assessment, wherein car purchase decision is made in BedDeM model.
[60] As anticipated in Section 4.2.2., acronyms have the following meaning: PRIV - Private home charging (7 kW) installed at own private parking lot.
RESID - Publicly-owned residential home charging (22 kW) at public parking lot (e.g., on-street parking).
COMM - Public charging in commercial parking lots (22kW)
RAPID - Rapid public charging (150 kW) used to cover long-distance trips.

optimal system deploys 6,000 to 14,000 RAPIDs by 2050, and each BEV uses them annually for 1.5 – 2.5 hours on average. Still, policymakers should consider tradeoffs between this cost-effective solution and providing more charging spots (each with lower power) to ensure sufficient charging spots at peak demand times. Further, increased CI accessibility away from home leads not only to more BEVs (+15%) and usage of such CI (+50%) but, in turn, also to more PC at home (+72%) to utilize long parking durations. Therefore, overnight charging options should be accompanied by sufficient CI in commercial locations and on highways. However, this piece of work is limited with respect to location-specific CI allocation, and spatially more detailed models could help provide such insights.

Charging stations with lower rated power are sufficient and more cost-effective for charging at home. Charging stations with higher rated power are advantageous in spots where faster charging (due to shorter parking duration) is beneficial throughout the day, as renewable energy from photovoltaics can be used more efficiently. Provision of overnight charging for tenants is most conducive to strong EV deployment. Still, public fast charging accessibility is necessary to cover long-distance trips, while its absence could be perceived as a “deal breaker” for many consumers. Public charging station at commercial complex further supports the EV roll-out for those who cannot charge overnight. We infer that the ability for consumers to charge overnight should be a priority but must be accompanied by sufficient CI in commercial locations and on highways. Essentially, the expansion of CI must consider the diversity in charging preferences and CI ownership. Therefore, a coordinated policy concept that integrates the different CI options is needed to achieve widespread EV uptake. Lack of BEV charging accessibility would make it more cost-effective to adopt hybrid cars in the short term, and hydrogen fuel cell cars in the long term, indicating alternate pathways to achieve the net-zero goal. However, in such scenario, the energy systemic impacts are diverse across the sectors. A journal paper is submitted based on these analyses (see also Annex 14.3.3).

Table 15: Charging infrastructure deployment in selected scenario

PRIV @ 7kW per charger				
Scenario	**Scenario Deskription**	**2030**	**2040**	**2050**
BAU Ref	Business-as-usual reference	151,000	224,000	370,000
NZC Ref	Net-Zero CO_2 reference	345,000	764,000	1,112,000
PC OPTI	OPTImistic PC access away from home	318,000	788,000	1,073,000
PC CONS	CONServative PC access away from home	361,000	726,000	1,040,000
PRIV-TEN	PRIVate HC enabled for TENants	357,000	929,000	1,430,000
RESID OPTI	OPTImistic RESIDential PC	344,000	794,000	1,101,000
RESID CONS	CONServative RESIDential PC	353,000	690,000	1,068,000
RESID ZERO	ZERO uptake of RESIDential PC	428,000	691,000	1,031,000
RESID @ 22kW per charger				
		2030	**2040**	**2050**
BAU Ref	Business-as-usual reference	8,000	14,000	25,000
NZC Ref	Net-Zero CO_2 reference	15,000	32,000	53,000
PC OPTI	OPTImistic PC access away from home	16,000	32,000	91,000
PC CONS	CONServative PC access away from home	15,000	32,000	41,000
PRIV-TEN	PRIVate HC enabled for TENants	11,000	63,000	101,000
RESID OPTI	OPTImistic RESIDential PC	16,000	51,000	139,000
RESID CONS	CONServative RESIDential PC	14,000	27,000	30,000
RESID ZERO	ZERO uptake of RESIDential PC	8,000	14,000	25,000
COMM @ 22 kW per charger		**2030**	**2040**	**2050**
BAU Ref	Business-as-usual reference	7,000	1,000	4,000
NZC Ref	Net-Zero CO_2 reference	7,000	15,000	20,000
PC OPTI	OPTImistic PC access away from home	7,000	20,000	35,000
PC CONS	CONServative PC access away from home	7,000	9,000	11,000
PRIV-TEN	PRIVate HC enabled for TENants	7,000	19,000	19,000
RESID OPTI	OPTImistic RESIDential PC	7,000	19,000	23,000
RESID CONS	CONServative RESIDential PC	9,000	13,000	13,000
RESID ZERO	ZERO uptake of RESIDential PC	10,000	16,000	16,000
RAPID @ 150 kW per charger		**2030**	**2040**	**2050**
BAU Ref	Business-as-usual reference	2,000	2,000	4,000
NZC Ref	Net-Zero CO_2 reference	2,000	4,000	9,000
PC OPTI	OPTImistic PC access away from home	3,000	5,000	14,000
PC CONS	CONServative PC access away from home	2,000	2,000	6,000
PRIV-TEN	PRIVate HC enabled for TENants	2,000	6,000	13,000
RESID OPTI	OPTImistic RESIDential PC	2,000	4,000	12,000
RESID CONS	CONServative RESIDential PC	2,000	4,000	8,000
RESID ZERO	ZERO uptake of RESIDential PC	2,000	2,000	6,000

Table 16: Selected indicators on charging infrastructure deployment by scenario

	Total charging capacity [kW] per BEV			#BEVs per private charger (PRIV)			#BEVs per public charger (RESID + COMM + RAPID)		
Scenario (see Table 17)	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
BAU Ref	5.6	4.6	4.6	2.0	2.2	2.2	18.3	28.1	24.7
NZC Ref	9.5	8.3	5.3	1.0	1.1	1.8	14.2	16.7	24.6
PC OPTI	9.0	8.1	5.3	1.1	1.2	2.2	13.8	16.0	16.8
PC CONS	9.7	8.5	5.3	0.9	1.0	1.7	14.5	17.2	30.4
PRIV-TEN	9.5	7.5	5.2	0.9	1.3	2.0	17.4	14.1	21.2
RESID OPTI	9.4	8.3	5.1	1.0	1.2	2.3	13.8	12.6	14.7
RESID CONS	9.5	7.6	5.2	1.0	1.2	1.7	13.5	18.4	35.9
RESID ZERO	11.0	9.8	5.9	0.7	0.8	1.4	26.3	30.8	65.0

In synthesis, the policy, business and territorial decisions referring to the type of charging infrastructure have very important implication for consumers' adoption of this technology. This, combined with the results of co-simulations, confirms the approach of PROBOUND which indicates that both facts and their interpretation matter.

10 Discussion

10.1 The implications of a high electrification trajectory

The baseline results in a high-electrification trajectory, in which BEV get to dominate sales and, with a delay, the stock, instead of a future technological pluralism. This result, obtained with heterogeneous bounded rational consumers, is in line with Li (2017, 65-66), which states that:

> *[in this simulated scenario] "electric vehicles are still more expensive than fossil fuel vehicles, and the rational economic choice would still be to select the cheaper option"*

and it goes on, when comparing the results of the adoption of electric vehicle by rational and bounded rational consumers, to state (*ibidem*):

> *"As their choices are more heterogeneous, a fraction of the market is not deterred by the increased costs of electric vehicles and purchases them in spite of their higher costs" [because] "non-price factors can often form strong determinants of decision making".*

In PROBOUND, the trend towards high level of electrification is accentuated, in different measures, by the discussed policies.
People purchasing EV sustain relatively high upfront purchasing costs of EVs, which has three dimensions:

1. price comparison with an "equivalent" ICE model;
2. affordability with respect to the budget constraint;
3. payment for superior features (environment, safety, silence and music enjoyment, enhanced driver assistance, etc.).

While the first is fully embedded in STEM prices, the second one is guaranteed in BedDeM: all agents purchase vehicles that are below their reserve price, thus can afford them, without over-indebtedness. The third is only partially covered in BedDeM.

Please note that in terms of Total Cost of Ownership, some BEV already have achieved the TCO parity. According to Goetzel and Hasanuzzaman (2022):

> *in 2020, mid-size and large electric vehicles were already close to price parity with conventional cars, even before subsidies provided by the German government. Small electric cars still required significant subsidies to be cost-competitive, however.*

While this is a general argument in favor for BEV, it has to be stated that a mainly bounded rational consumer will not consider TCO, as purchasing costs, and operational costs will be sepated in the mental accounting. Thus, for purchasing decisions the initial price tag is of much more significance as the TCO.

Outside the mobility sector, because of the assumed fixed total amount of mitigation in a given time frame, the electrification in the mobility sector reduces mitigation efforts in other parts of the energy system. If, instead, the reaction of bounded rational consumers for other decisions (e.g. building insulation, rooftop PV in private houses, etc.) would rather be enhanced by bandwagon effects, the actual total mitigation would rise and Switzerland would reach net zero before 2050.

10.2 The most desirable policies

Policy designs have differentiated effectiveness. Over time, their ranking in terms of the increase of sales changes. The cumulative effects reflected on the fleet depends on the full timeline. The use of the fleet impacts the cumulative CO_2 emissions, which are linearly related to temperature increases (in contrast to single-year target achievements) (Matthews, et al 2018; IPCC, 2018).
Balancing the different perspectives, one might indicate the following priority policies:

1. the provision of opportunities for driving trials of BEV;
2. the support to fast charging;
3. mandatory information at dealerships;
4. a communication campaign raising the importance in decision-making of energy labels.

In the first year of introduction, the most successful policies are the following:

1. the penetration of "information bubbles", where a conversation about pros and cons of different technologies takes place,
2. increasing the visibility of fast charging stations through road signs.

These policies are particularly important if the current real-world trend is not considered to be in line with the net zero goal, because they act as an insurance against undesirable developments (e.g., lack of action in other sectors, unavailability of price-competitive climate-neutral fuels, etc.) by accelerating the electrification of passenger transport.

Since they rely on various bounded rational cognitive biases, one could say that, within the limits of the models and of the bundle of policies actually implemented, mobility-system level effects can be provoked by the "confirmation bias", the "egocentric bias", the "status quo bias" and the "salience bias" in individual decision-making[61]. In laymen' terms, the fact that people take decision in a specific moment of time and space means that proposing information in that exact moment and place is highly influential, but also that previous status quo, own experience and exposure to media that share an initial "prejudice" does frame that moment. In particular, by acting on the media environment before

[61] For an explanation of these biases, see the Section 2 and its references, including e.g. Pohl (2004).

any intention of purchase is expressed, one can influence the initial prejudice which will be then defended by routine dismissal of contrasting new information.

This is not to say that other biases are not important; on the contrary, this project, in its pioneering way to connect individual bounded rational choices to policies, strongly suggest the interest to further research in the field.

10.3 The role of plug-in hybrids in the transition

Plug-in hybrids, although present in the objective market, do not take off as major vector of electrification, in the baseline and under policies. This result is technically due to the limited size of the subset of the objective market that every consumer takes of the entire market in order to more closely evaluate the alternatives and the paucity (and price positioning) of models that are exclusively hybrid plug-in. Indeed, in the Swiss real market, very few models are only hybrid plug-ins. Most of current sales are in models that have several motorization alternatives.

Moreover, their main advantage (the flexible mix of fuel and electricity) lead to a variable and uncertain utilization of energy. Whether the driver will use mostly electricity or a fossil fuel depends on behavioral choice, which in principle could be influenced by bounded rational policies. In a net zero perspective, the contribution of plug-in hybrids strictly depends by such micro-choices. It would be interesting to have such data for Switzerland. In other countries, the data tend to indicate that plug-in hybrids make in practice few kilometers with electricity[62] and, overall, their emissions (due to their weight and size) are far from zero. Accordingly, some policymakers are stopping subsidizing this typology and, according to the EU Commission proposal, they also will be banned from 2035. By contrast, in the model, they are offered by manufacturers for the entire period of simulation.

10.4 Implications for the diffusion of hydrogen fuel-cells vehicle in private mobility

In the baseline and across all policies, the diffusion of hydrogen fuel-cells vehicles fails. The key determinant is the decentralized decision-making, with hydrogen not taking off because of insufficient fall in price. If for any reason the presence of hydrogen fuel-cells vehicles in the private mobility would be advisable (e.g. as seasonal storage to cope with the high share of renewable electricity), policymakers should explore the possibility of utilizing policies leveraging bounded rationality with such vehicles in focus, in parallel to manufacturers proposing compelling models at adequate prices, and to an adequate infrastructure of refilling.

10.5 Implications for public transport

The public transport does not need to be afraid of the taking off of electric vehicles: the passenger km would not be affected a lot (and actually they would be positively), most likely because for long trips people may choose a train over an electric car. Moreover, some of the policies directed at BEV may actually be redesigned to fit the public transport and bring additional demand to it. A partially similar approach has been proposed in Bektas, Piana and Schumann (2018).

[62] See e.g. Chakraborty et al. (2020) and https://www.hotcars.com/never-charge-plug-in-hybrid-vehicles/

10.6 Limitations due to the focus on households

Alongside all the project, the stock of vehicle has been entirely attributed to households, which were the only institutional sector to buy. It's clear that business fleets, rental services, taxis and other players are, by contrast, very relevant. They have been excluded from analysis because one can expect monetary incentives, in particular in fiscal terms and amortization, to exert an influence on professional purchasers, more than their individual psychology. Because of weight of non-households on the real market, some numerical results of policies should be considered to be an over-estimation. Conversely, it should be noted that, as driving test and personal exposure to experience and "information bubbles" have been demonstrated as impactful, the diffusion of new types of vehicles, including BEV, in a non-household context would synergyze with household purchases.

10.7 Limitations due to the focus on new cars

During the project, obtaining microdata about the used car market has turned out to not to be possible. So the framework, which had been prepared to include trade of used cars through dealership (but not with the double decision of selling and buying), has been exclusively used for new cars. Similarly, the scrapping decisions, which at a point were explored as independent from purchase, have been kept very simple, with scrapping occurring after purchase automatically, to the effect that the model has not explored the potential to significantly reduce the stock of vehicles. This is in line with e.g. EP2050+ stock. In other terms, further research may be addressing how to cope with the market for used cars and to explore policies aimed at reducing the stock itself. It should also be mentioned that agents can have two or more cars but they tend to use (for their trips) only one (which is superior to the others in some subjective respect) to the effect that in the stock there are some cars which cumulate few km made, which, in the model, does not favor replacement.

10.8 Learning outcomes

The effectiveness of policies may well depend on the baseline, which embeds assumptions about the general discourse in media and public debates about different technologies. If in the population we have a negative view (a lot agents filter out EVs in the first stage), policies addressing “filtering” aspects are helpful to create a larger pool of interested people that will bring to the next stage (and larger parts of them will buy). If (enough) people already include EVs in their short list of alternatives, the first group of policies loses effect and influencing decision-making becomes more important. This, in general, is an important aspect for policy making in the light of bounded rationality. Policy design must ensure both that desirable outcomes (from the policy making perspective) are, on the one hand, considerable options (i.e. they are perceived as options in the perception phase), and, on the other hand, the desirable options are attractive compared to alternatives for the decision-making phase.

Under the current baseline, all policies have a positive effect in the first year of implementation. This was not the case in the entire time of the project, since at a point the baseline itself contained a very high share of BEV in sales already in 2022, leading to some perplexities by the Advisory Board. A different media environment was implemented as input (keeping all parametres of agents as they were before), leading to the current baseline.

Accordingly, the first recommendation is to analyze the public discourse to identify the prodromic aspects of a baseline without policy intervention. If the public discourse and its reflection in information bubbles (e.g. in newspapers, social networks) can be considered as very negative, leading to downright dismissal as plausible alternative, thus hindering a specific decision-making process, then policies acting on items of the latter will not be effective. For instance, incentivizing charging station becomes not effective in producing new sales of EVs, if people are dismissing EV as, for instance, dangerous and environmentally damaging. In this setting, policies penetrating information bubbles are very relevant.

In principle both types of policies are important. However, it first requires a large enough pool of people being interested (considering it an option, i.e., have it in the shortlist resulting from filtering). A first batch of policies always needs to address this.

If sufficient people consider EVs as an option, then policies influencing the decision-making will have an effect (not before) and can ensure that a favorable option ends as an actual demand. If it remains open what share of the Swiss population currently already considers EV as a valuable option in the shortlist, it cannot be drawn which policies are now the preferable.

On a broader perspective, several policies increase in the short term the share of EVs in sales, then in the fleet and its usage. To the extent electrification of transport is an advisable development, these polices, within the models, exhibit some degree of effectiveness.

10.9 The achievements of the PROBOUND project

The research project PROBOUND has explored the possible widening of the toolbox of policies for the energy transition. Based on literature that identified bounded rationality as a key aspect of human behavior, it has gone beyond anecdotes and, in themselves very valuable, experiments on single issues to shift the theme towards impacts in national aggregates. Policies leveraging, not negating or mitigating, bounded rationality have been explored at three levels:

- touchpoints / general directions,
- policies and
- (sub)designs of each policy.

Key parameters of the national mobility system and energy system of Switzerland have been demonstrated to be impacted by policies and designs in a quantitative manner, drawing on individual socio-cognitive decision-making. With the diffusion of these results, the project is going to contribute to a very important debate on how insights from psychology and other Social Sciences and Humanities can influence model structures, parameters, and results.

In terms of modelling strategy and refined tools, the tight co-simulation of an agent-based model with a comprehensive energy system model, with all its technical difficulties, has been demonstrated to be feasible. It has allowed a large number of scenarios to be generated and compared.
The high level of innovativeness of the project has been incorporated in two PhD proposal, currently in their very late stage of maturity.

Given the timing of the achievement of the numerical results, it is not surprising that the publications already made with the funding of the project have been concentrating, with some exceptions, on modelling and methodological aspects.

From a policymaker point of view, this project has scratched the surface, showed some deeper insights, and provided a field for many relevant questions (and a lot of numbers to be interpreted). The sedimentation and robust questioning of the model results – but also of the bounded rationality framework as such – is part of a process at the interface between science and policy-making that will continue to be relevant in the next years.

11 Conclusions and outlook

The PROBOUND project aimed at understanding bounded rationality (BR) in the mobility sector and investigated a set of policies (and their multiple designs), leveraging consumers' BR, in the Swiss personal mobility decision-making. The impacts of those BR policies have been quantified for the Swiss energy system. Through a literature review, we identified a number of BR directions, which applies overall but with special intensity in the case of totally new technologies with divergent opinions surrounding them, such as battery electric vehicles (BEV). After extensive original exploration, we shortlist a set of BR polices, targeting driving tests and other personal experiences surrounding or preceding the decision-making process, the judgmental context, the perception, the simplified information delivered by energy labels, as well as price signals. Eight BR policies have been articulated and crafted into 21 different designs, and their impact on the Swiss passenger mobility have been assessed. The selection of these BR policies takes into account the flexibility of the analytical tools proposed in this project. We use two existing analytical models, namely an agent-based model of Swiss mobility sector (BedDeM) and an energy system model of Switzerland (STEM), significantly developed during the project.

To compare the effects and impacts of BR policies, we established a Baseline scenario. For BedDeM, the Baseline scenario include manufacturers' announcements and new models, with a complete phase out of conventional internal combustion engine from year 2040. From the energy systemic perspective, the baseline scenario aims to achieve the net-zero goals by 2050. In the baseline scenario, the share of BEV car in the total car fleet reaches to 16.6% in 2030 and 82.8% in 2050. In short term, almost all BR policies have positive effects and increase the penetration of BEV between 3 and 26 percentage points from the baseline. Both policies providing price signals and non-price policies are effective in modifying purchases and behaviors. The effectiveness of the two types of policies is in the same order of magnitude. These BR policies induce a high use of public transportation.

From the BR policies, the average CO_2 emission reduction in year 2030 is from 0.06 to 1.1 million tons in the entire transportation sector in 2030 with respect to the baseline, depending on the BR policy design. Obviously, some of these policies do incur high energy system cost due to purchase of BEV (in early decades, in which their price is not fallen enough) and due to the development of corresponding infrastructure. However, they reduce the need for CO_2 mitigation measures in building and industrial sectors as the (fixed) 2030 CO_2 reduction target is met with the BEVs. In the long term (2050), the impact of the BR polices are negligible in the energy system because of BEV market saturation and the assumptions on unavailability of ICE cars. Nevertheless, the short-term impact of BR polices continues to be felt in long term, and reduces about 0.1-0.6 million CO_2 emissions in year 2050 due to the BR policies.

Policy design differs in terms of impacts thus it can be stated that the parametrization of a policy is as important as the type of policy itself. The discussions on policies (and their relative advantages and disadvantages) need to keep into consideration a fine-tuning of the policy design, when we move from philosophical fundamental differences (and the mapping of which stakeholder would be activated, which tend to be the same for all designs of the same policy) into a discussion about their effectiveness. Furthermore, it has to be stated that in this study the policy design and evaluation has been strictly limited to the mobility sector, thus no effect of policy boundles for different sectors have been taken into account.

Additional scenario analysis on charging infrastructure using STEM model from a social planners perspective shows that a coordinated charging infrastructure (CI) strategy could accelerate uptake of battery electric vehicle (BEV) in selected consumer groups. On the average, each electric car needs about 5.5 kW charger. In terms of charger distribution density, 1.4 - 2.3 BEVs per private charger of 7-22 kW size and 15 - 65 BEVs per public charger of 22-150 kW size, depending upon the scenario assumptions. Overnight access to charging station enables the strongest BEV deployment (+31% in 2050 compared to a reference scenario). Increased accessibility of public charging station in non-residential locations makes it financially conducive for tenants to buy more BEVs (+61%), which also requires more CI capacity in residential areas (+66%) for overnight charging. While slow charger is cost-effective at home, fast (high power) charger in commercial areas enables more efficient use of solar PV electricity.

On the broader picture of the co-simulation, the most impactful policies, in terms of their effects in 2030, are the provision of opportunities for driving trials of BEV (+26% in market share), support to fast charging (+22%), mandatory information at dealerships (+6%). Energy labeling policies can be either effective (+4%) or not (-0.5%) depending on the BR policy design. In the first year of introduction, the most successful policies include the penetration of “information bubbles”, where a conversation about pros and cons of different technologies takes place (+15%), and increasing the visibility of fast charging stations through road signs (+14%).

These policies are particularly important if the current real-world trend is not considered to be in line with the net zero goal, because they act as an insurance against undesirable developments (e.g., lack of action in other sectors, unavailability of price-competitive climate-neutral fuels, etc.) by accelerating the electrification of passenger transport.

Key parameters of the national mobility system and energy system of Switzerland have been demonstrated to be impacted by policies and designs drawing on individual bounded rational socio-cognitive decision-making. With the diffusion of these results, the project is going to contribute to a very important debate on how insights from psychology and other Social Sciences and Humanities can influence model structures, parameters, and results.

The methodologies developed in the project can also be transferred to other areas, where private actors, which are more likely to be affected by BR effects, make decisions and these decision-making effects the overall energetic and economic development.

12 Publications

List of published material funded by the PROBOUND project:

Luh, S., Kannan, R., Schmidt, T. J., Kober, T. (2022). Behavior matters: a systematic review of representing consumer mobility choices in energy models, Energy Research and Social Science. 90: 102596 (23 pp.). https://doi.org/10.1016/j.erss.2022.102596

Luh S, Kannan R, McKenna R., Schmidt T.J., Kober T. (2023). Electric vehicle charging infrastructure in a cost-effective net-zero energy system: policy options and cross-sectoral implications (submitted to journal)

Luh, S., Kannan R, McKenna R., Schmidt T.J., Kober T. (2023). Systemic implications of modal shift for achieving a net-zero energy system (working paper, to be submitted to journal)

Luh, S. (2023) Decarbonizing Swiss road passenger transportation – an energy systemic and consumer perspective, PhD Thesis (to be submitted to ETHZ).

Nguyen, K., (2023). Case study: The model of purchasing vehicle, chapter 7 of "A Behavioural Decision-Making Framework for Agent-Based Models", PhD Thesis accepted and successfully defended at Utrecht University.

Nguyen, K., Piana, V. and Schumann, R. (2022). Simulating bounded rationality in decision-making: An agent-based choice modelling of vehicle purchasing, Proceedings of the Social Simulation Conference, Sep. 2022. Available at http://publications.hevs.ch/index.php/publications/show/2933

Brückmann, G., Berger, S., Caviola, H, Hahnel, U., Piana, V., Sahakian, M., Stadelmann-Steffen, I. et al. (2023). Towards more impactful energy research: the salient role of social sciences and humanities, PLOS Climate. https://doi.org/10.1371/journal.pclm.0000132

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14 Annex

14.1 The technical advancements in 2022

In summary terms, in the final year of the project, the following advancements have been introced in the models.

In BedDeM:

- ✓ A new **module** in BedDeM for purchase decisions
- ✓ Re-instantiation of **Triandis' SSH model** for the new module, providing consistency between the trip-decision module and the purchase module
- ✓ Widened coverage of **bounded rationality features** in the agent's perception and decision-making
- ✓ An **Objective Market** of models, drawing on real data and announcements.
- ✓ An empirically-grounded **Opinion environment**, with agents exposed to different media in proportion to their answer to a real questionnaire (SHEDS)
- ✓ The Opinion environment flexibly containing topics of discussion, related to alimentation and brands
- ✓ Inclusion of **Dealerships** as part of the Opinion environment entering in (some of the) topics of discussions
- ✓ An extensive **operationalisation** of different **policy designs**

In STEM:

- ✓ Elaborated **consumer segmentation** and full integration of them into STEM
- ✓ Differentiating **trip distances** to better reflect EV charging requirements
- ✓ Implementation of **multiple EV charging infrastructure options** (home charging, public charging in residential areas, public charging in commercial areas, and rapid charging)
- ✓ Endogenous approach for **advanced charging schedules**
- ✓ Inducing **non-cost behavioral aspects** in the optimization model, i.e., time and comfort
- ✓ Enabled option for **multi-criteria optimization** decision
- ✓ Endogenous **modal shift** option

14.2 An overview of BedDem related developments and applications

As described in Bektas, Nguyen, Piana and Schumann (2018), the core element of the BedDeM platform is a agent based simulator, written in Java with RePast library, complemented by key concepts from Triandis' Theory of Interpersonal Behavior . This promotes communication with scientists from diverse research backgrounds (computer scientists, economists, psychologists etc.) about different scenarios.

The BedDeM (Behavior Driven Demand Model) is a simulation platform embedding a socio-cognitive agent based approach, built on the key theoretical tenets of multi-agent cognitive system, in which every individual agent is capable of making psycho-socially sound decisions and takes into account both objective and subjective elements (e.g. weight for evaluation criteria of alternatives) (Nguyen and Schumann, 2018; Nguyen and Schumann, 2021). It has been used to evaluate policies to increase the use of train (Bektas, Nguyen, Piana and Schumann, 2018). A meso-level empirical validation approach for agent-based computational economic models drawing on micro-data has been proposed using the model as example (Bektas, Piana, Schumann, 2021). It can be considered as a proven tool used at HES-SO Valais/Wallis since 2017.

Key features are the following: a socio-cognitive multi-agent platform, a direct 1:1 relationship with micro-data from SHEDS and from Mikrozensus, an approach to scale up to national values based on considering the agent as a sample of the national population.

14.3 An overview of STEM related developments and applications

14.3.1 Key features of the Swiss TIMES Energy systems Model (STEM)

The Swiss TIMES Energy systems Model (STEM) covers the whole Swiss energy system from resource supply to end use sectors through energy conversion and distribution (Figure 26). It has a long-term horizon (2010 – 2050) and incorporates an hourly intra-annual resolution for three typical days in four seasons (winter, spring, summer and autumn). STEM optimizes the whole energy system to supply exogenously given energy service demands (e.g., space heating, mobility demands) at the lowest cost. It is a well-established model developed at PSI over a period of 10 years.

Figure 26: Salient features of STEM

- Whole energy system model with detailed electricity sector
- Long time horizon with hourly time steps being able to analyse summer/winter shifts and short term flexibility
- Representation of long-term investment choices and short-term operational decisions
- Fully calibrated to the latest Swiss energy and electricity statistics from SFOE
- Explicit electric interconnectors with the neighbouring counties
- Aggregated electric grid topology
- Unit commitment and advanced storage algorithms
- System flexibility options and sector coupling including modelling of ancillary services
- Extensive new and emerging technological options
- Dynamic model and optimisation for entire time series (i.e. energy transition pathways)
- Existing and future policies and regulatory targets

The following methodological features are particularly valuable for this project:

- Detailed electricity sector with all existing power plants in Switzerland and dedicated interconnectors to the four neighboring countries, as well as a rich portfolio of possible new power plant options,
- Electricity grid topology with fifteen aggregated grid nodes and 300 transmission lines connecting these nodes to account for congestion, provision of ancillary services (primary, secondary and tertiary reserve), distributed generation and flexibility options related to supply, demand and storage, as well as implementation of the unit commitment algorithm for dispatching the power plants (such as minimum stable operating level, minimum online/offline times, ramping rates, start-up and shut-down costs, part load efficiency losses, extensive storage cycling)
- Very extensive details of current and future technologies for heating and mobility sectors including various technologies for advancing the electrification of the demand sectors and sector coupling. The transport module includes battery charging control options for e-mobility, fast charging and refueling infrastructure, vehicle to grid, etc.,
- Thermal, electrical and hydrogen storages, synthetic fuel production, carbon capture (utilization) and storage (CC(U)S) for energy and industrial applications,
- Consistent sets of future trajectories on demand drivers, technology learning, energy prices, resource potential, which can be easily updated based on socio-economic and techno-economic developments.

TIMES has been developed under the Technology Collaboration Programme ETSAP (www-iea-etsap.org) of the International Energy Agency (IEA) and is a proven and widely used modelling framework (e.g. for IEA's flagship publication of Energy Technology Perspectives). Therefore, we also benefit from wider international expertise. Being anchored in IEA-ETSAP, the model is always up-to-date and includes all the most recent mechanisms needed to answer questions from policy makers and stakeholders. Thus, STEM is a state-of-the-art energy system model for Switzerland, unique in its kind.

The model produces numerous outputs on the Swiss energy transition, capturing broadly technology pathways, emission trajectories, investment needs and policy costs. A comprehensive documentation of the model features and model results are available in Panos et al. (2021), while input data and key assumptions can be also found in Marcucci et al. (2021) and Kannan et al. (2022).

14.3.2 The transport sector in STEM

The transport sector in STEM has both passenger and freight transportations. It has various transportation modes, such as personal motorized mobility (cars and two-wheelers), public road transport (bus, trams), road freight, rail transport for passenger and freight, and domestic aviation. A schematic of the transport module in STEM is shown in Figure 27.

The demands for passenger and freight transport are adapted from the trends described in the reference scenario of the Swiss Federal Office for Spatial Development (ARE, 2021). The passenger mobility pattern is based on the latest available Swiss mobility survey (ARE, 2017). For the baseline scenario, energy prices from the IEA's Sustainable Development Scenario are applied – reflecting global efforts on climate change mitigation (IEA, 2020). Similarly, the imported electricity prices at the hourly level are based on two EU scenarios with "decarbonization" trends (ENTSO-E, 2018). Table 17 shows an exemplar of characterization of medium size car technologies in STEM based on Sacchi et al., 2022. Table 18 summarizes the energy price assumption in STEM. Techno-economic characterization of vehicles technologies are provided in Kannan et al., 2022.

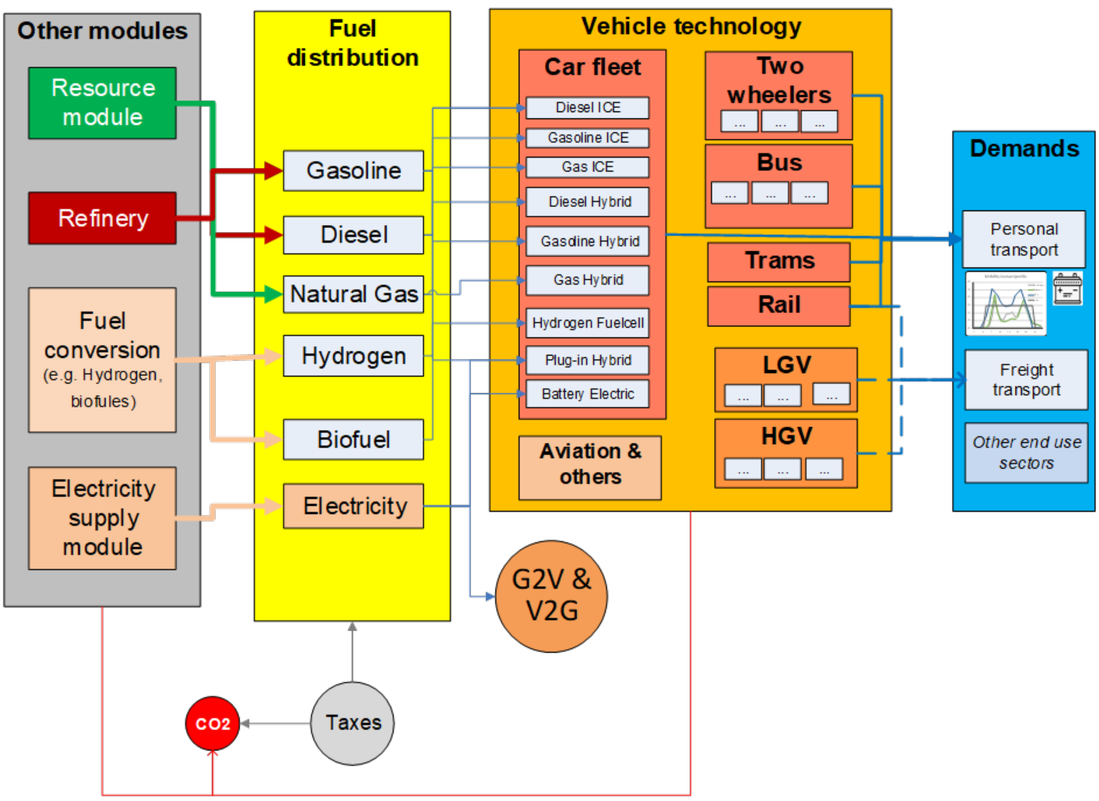

Figure 27: An overarching schema of mobility module in STEM

Table 17: List of vehicle type and characterization for medium size (60-100 kw) car by vintage

Vehicle type (Fuel / Drivetrain)	Vintage year	Power electric motor	Battery size or tank size	Fuel efficiency (tank to wheel)	Purchase cost	Maintenance cost	Driving range per charge / fuelling
		KW	*kWh*	*MJ/km*	*000' CHF*	*CHF/year*	*km*
Petrol ICE	2020	2	0	2.5	42	1043	449
Diesel ICE		2	0	2.3	48	1043	554
Petrol hybrid		31	0	1.3	44	696	726
Diesel hybdrid		31	0	1.3	44	696	822
Petrol plug-in		81	4	1.2	45	696	397 (59)
Diesel plug-in		79	4	1.2	45	696	454 (67)
BeV		144	53	0.6	53	1391	242
FCEV		139	0	1.1	64	1486	530
Petrol_ICE	2030	7	0	2.2	42	1043	458
Diesel ICE		7	0	2.0	48	1043	546
Petrol_HYB		30	0	1.1	43	696	717
Diesel hybdrid		30	0	1.1	43	696	812
Petrol plug-in		77	9	0.9	44	696	319 (99)
Diesel plug-in		76	9	0.9	44	696	359 (112)
BeV		136	65	0.6	49	1391	334
FCEV		131	0	1.0	54	1414	549
Petrol_ICE	2040	11	0	1.8	42	1043	453
Diesel ICE		12	0	1.8	47	1043	523
Petrol_HYB		29	0	1.0	43	696	690
Diesel hybdrid		29	0	1.0	43	696	781
Petrol plug-in		74	15	0.7	44	696	260 (131)
Diesel plug-in		73	15	0.7	44	696	286 (144)
BeV		128	73	0.5	46	1391	416
FCEV		123	0	0.9	49	1391	563
Petrol_ICE	2050	16	0	1.6	42	1043	429
Diesel ICE		16	0	1.6	47	1043	483
Petrol_HYB		28	0	0.9	42	696	641
Diesel hybdrid		28	0	0.9	42	696	725
Petrol plug-in		70	22	0.5	44	696	236 (164)
Diesel plug-in		70	22	0.5	44	696	250 (173)
BeV		121	75	0.4	45	1391	477
FCEV		117	0	0.7	46	1391	571

Source: Kannan et al., 2022

Table 18: Energy price assumption in STEM

Energy carrier	2020	IEA's *Reference* (CHF_{2010}/GJ)			IEA's *Climate* (CHF_{2010}/GJ)		
		2030	2040	2050	2030	2040	2050
Crude oil	8.8	18.5	20.7	22.8	11.0	10.7	10.3
Natural gas	3.1	9.3	10.4	11.0	7.4	6.9	6.5
Biodiesel / PtL diesel*	42.7	49.7	52.4	55.0	56.4	65.7	70.8
Ethanol / PtL gasoline*	30.4	39.4	41.9	44.3	48.2	59.2	64.1
Biogas	17.0	19.1	22.3	24.4	20.6	24.2	27.4
Electricity**	16.7	21.2	20.3	18.0	27.7	27.7	28.9
Hydrogen	26.9	40.1	42.7	44.7	41.6	44.4	52.1

** Price refers either to diesel/gasoline from biogenic sources or imported e-fuels*

*** Electricity prices are averaged across the neighbouring countries and across the hours of a year*

Source: Kannan et al., 2022

14.3.3 Working paper STEM #1

Sandro Luh et al. (2023) Electric car charging infrastructure: assessing policy options for achieving net-zero cost-effectively (submitted journal paper).

14.3.4 Working paper STEM #2

Sandro Luh et al. (2023) How can modal shift support the systemic shift towards net-zero? (working paper)

14.4 The contribution of the PROBOUND project to the methodological issues in coordinating simulations of the Swiss Energy System models

14.4.1 Context: why to coordinate models of the Swiss Energy System

Models of the Swiss energy system approach from different angles a nexus of social, economic, technical, environmental and institutional actors, actions, opportunities, constraints, results and issues. They do this typically with the conceptual and mathematical formulations that are currently cutting-edge, with different degrees of internal complexity and admitted boundary conditions. In this respect, they inevitably select, simplify and numerically determine a certain number of variables. Some of these aspects are very detailed and based on an extensive review of empirical and theoretical studies, other variables are less in focus, with significant degree of aggregation and simplification.

To get an overall systemic view, theoretically one could increase one's model complexity with all possible additional variables and sub-modules but there is the risk that the final model will be either too complex to provide interpretable results or will contain modules that are too simplistic to adequately represent specific target areas. A different strategy, particularly suitable when other

models are already existing and having different foci, is to link two or more models so as to grasp the best of two (or more) worlds.
In general, this strategy increases the expressiveness of the outcomes, since it allows:

1. to capture more variables in an adequate manner;
2. to match different temporalities, with some models having a wide time step (e.g. 5 or 10 year) and be capable of the projection into the deep future while others have more frequent decision-making and responses (e.g. yearly or below the year), with the resulting higher flexibility and space for faster reactions;
3. to match different territorial level (e.g. international, national, sub-national).

In particular, when models are supposed to provide insights for policy purposes, linking models allows for certain policies to be introduced in one model but their immediate and far-reaching consequences are computed and become visible in the whole suite of models. Policies that can be tested coming from a wider toolbox, which strengthen the meaning of their ranking (e.g. in terms of effectiveness).

In other words, model coupling has the advantage that each model can remain its core focus, while the combined approach of complementary models allows for a deeper understanding of the effects of developments and potential policies.

Linking models is particularly interesting when some models have analytical strength and produce optimal results (under some assumptions and objective functions), while others embed realistic descriptions of human decision-making.

14.4.2. How to coordinate simulations: some general remarks

A basic way to coordinate simulations is simply the alignment of input data on demographics, macro-economic drivers and spatial development. This can refer to a single year in the past or to a full trajectory of future values[63].
A more advanced coordination is the provision of data from one model to another in a sequence. The first model is executed and provides a trajectory of values that are used by the second one. These values can be aggregate (possibly requiring an intermediate disaggregation) or disaggregate (possibly requiring re-aggregation). In a previous research program, the Joint-Activity "Evolution of Mobility: A Socio-Economic Analysis" between SCCER CREST and SCCER Mobility, four models were sequentially linked (STEM, BedDeM, MATSIM and SWISSMOD), with aggregated values from STEM (such as the fleet stock) delivered to BedDeM (which carried out a disaggregation to agent level of the stock). In a following step, the data came back to STEM, often following a re-aggregation (e.g. in segments), for energy system-level consequences and analyses[64]. In a different project, STEM has been linked to a macroeconomic model (Kober et al., 2020) to assess the economic impacts of energy polices.
A third level of tighter coordination is the co-simulation, whereby one model provides a first batch of data parameters, referring to a certain year and attributes, to another model as the ground for simulation. The latter feedback again to the first, so that its computation can be iteratively updated for

[63] The alignment can be narrower or broader, e.g. by including variants for global climate change developments.

[64] See the technical report on model linking (Schumann et al., 2018) and the final report of JA Evolution of Mobility (Piana et al., 2020).

the subsequent periods. Thus, in their simulation over the entire time period, both models gets executed in parallel, exchanging and therefore synchronizing various times.
The linked model can share the same methodological frameworks or take advantage of different modeling philosophies to address specificities of the domains each of them focus. For instance, it's appropriate to have a centralized decision-making and long-term perspective in energy production through nuclear power, whereas the subject matter of mobility is characterized by heterogeneous investment decisions in mobility and by direct emissions linked to actual use of the vehicles (subject to trip-level modal choices).

14.4.3. The PROBOUND project

This project tightly co-simulates two models, along the lines of the third level described in the previous chapter. The models are the following:

1. STEM, the Swiss TIMES Energy system Model, developed at the PSI-EEG, is a technology rich, cost optimization model of the Swiss whole energy system (Panos et al. 2021; Kannan and Turton, 2016; Kannan and Hirschberg, 2016). The model optimizes technology and fuel mix to meet the given energy service demands based on competing energy pathways while fulfilling energy supply and environmental constraints. It sheds powerful insights on long term development of the Swiss energy system. The transport sector in STEM has an extensive type of vehicles with a combination of different drivetrains and fuels. For any emerging vehicles such as fuel cell and battery electric cars, an aggregate infrastructure is included for both private and public transportation. This modelling framework minimize cost of energy supply and demands from a social planner's perspective. However, this approach ignores heterogeneous non-cost based decisions, which are important for the personal mobility choice.

2. BedDeM, the Behavior-driven Demand Model, developed at SILab (HES-SO VS), is an agent-based model of the Swiss population, embedding a psychologically realistic human decision-making model (Nguyen and Schumann, 2019; 2019b; 2020). Agent-based models are an emerging economic modelling tools allowing for a wide heterogeneity of individualized state values, reflecting personal and idiosyncratic history, *modus operandi*, knowledge elaboration, and outcome production.

The aforesaid two modes were developed independently and can operate in a stand-alone mode. However, by linking them, one obtains the following advantages:

1. the broad and comprehensive view of the Swiss energy system frames and receives bottom-up inputs from an extremely detailed and articulated decentralized decision-making at household level;
2. the complexity of heterogeneous and interacting agents, whose choices and cumulative stocks are aggregated over the national level and over the years
3. a large spectrum of possible policies and influences of bounded rationality over decisions in the mobility sector can be tested, compared and ranked according to different criteria. At the same time, their implication to the energy transition can also be quantified with the co-simulation framework.

In methodological terms, the involved models are quite different. STEM embeds the rationality of a social planner, who, aware of the damages of climate change, has chosen a climate target of net zero emissions in a certain year of the future. It takes key decisions every five or ten years of simulated future time, reflecting strategic decision-making at the beginning of the periods and its consistent implementation. BedDeM hinges on a high number of independent agents, each representing a household, in the logics of the statistical sample in empirical surveys, according to which every "respondent" is then weighted to produce totals at the national level, i.e. leading to a representation of the population. Every agent takes decisions, based on its history, preferences, perceptions, habits and other components. Decentralized decision-making is largely myopic, in line with the bounded rationality paradigm. The effects of such piecewise decision-making cumulate over time and produce trajectories, whose emission implications can be computed.

All their differences notwithstanding, including their programming languages, libraries and tools, they were successfully coupled already in the previous research JA Mobility: the carefully crafted exchange of data does not require the homogenization of the internal structure of the models, which allows, in contrast to some literature statement (Horschig, Thrän, 2017), to combine the strengths of the two approaches, in a sort of a hybrid approach.

Indeed, with respect to the general methodological enterprise of coupling energy system models and agent-based models, there are few examples[65] (Thiel et al., 2016; Blanco et al., 2019; Tattini, 2018). However, these model couplings do not apply an iterative approach, i.e. data exchange is not bilateral. In this respect, PROBOUND is going beyond the state-of-art. A more structured systematic review paper on methods for representing consumer mobility behavior in energy models is submitted by members of the PROBOUND project to a peer-reviewed journal (Luh, et al., 2021).

[65] In other directions, ABM are coupled with system dynamics models (see e.g. Shfiei et al., 2013; Łatuszyńska, 2018; Scorrano and Danielis, 2021), with general computable equilibrium models (see e.g. Niamir et al., 2020) and with multi-level perspectives (Wu et al, 2020). Some see agent-based models as evolution of optimisation-based models (e.g. Ma and Nakamori, 2009; Shchiptsova et al., 2016).

14.4.4. Overview of the two models

14.4.4.1. STEM – basic description

The Swiss TIMES energy system model (STEM) is the energy system model of Switzerland (Kannan and Turton, 2016). The whole energy system is depicted from primarily resource supply to end-use Energy Service Demands (ESDs), such as space heating, lighting, and personal/freight transport (in vehicle- or ton kilometer). The model represents a broad suite of energy and emission commodities, technologies and infrastructure as illustrated in the reference energy system below. The model has a time horizon of 2010-2050+ with an hourly representation of weekdays and weekends in four seasons.

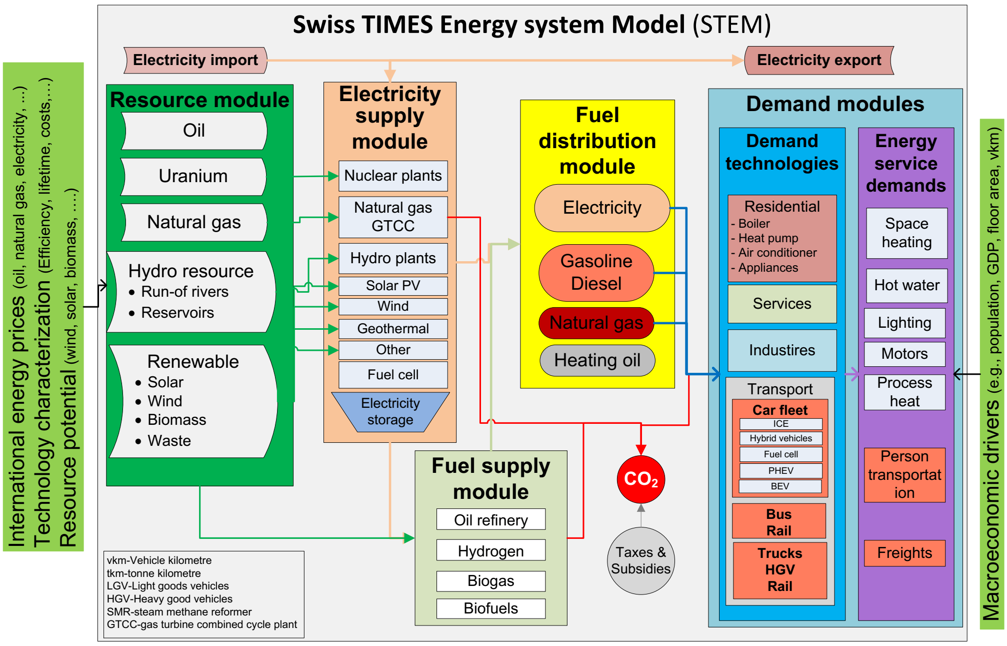

Figure 28: STEM model overview

The model is used to identify the least-cost combination of technologies and fuels to supply the ESDs while fulfilling technical, environmental and policy constraints (e.g. energy resource potential, CO_2 mitigation policy, emission standards). The key model outputs include technology investment and fuel mix across all the sectors, which are aggregated to report primary energy supply and final energy consumption, seasonal/daily/hourly electricity demand and supply by technology type, CO_2 emissions, cost of energy supplies, and the marginal cost of energy and emission commodities, among others.

The transport sector in STEM covers ten mobility modes, *viz*. cars, buses, rails, and trucks (Kannan and Hirschberg, 2016). It has a range of existing and future vehicle technologies with a plurality of drivetrains and fuels. The model includes pure battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), charging of which can be controlled.

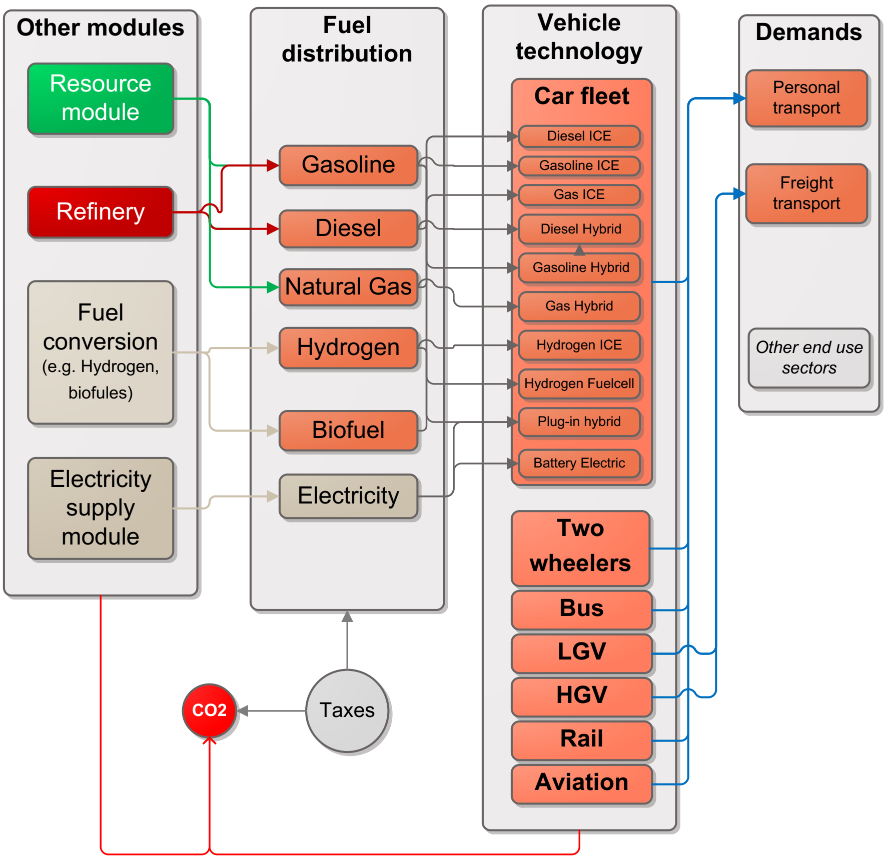

Figure 29: Transport module in STEM

14.4.4.2. BedDeM – basic description

BedDeM is an agent-based simulation platform. In its implementation to mobility, it contains several thousands of agents (simulated people) who take decisions, based on individualized state-data, choice parameters and history. Within each agent a decision-making process is the culminating part of a broader setting, in which perception of market and of other agents play an important role. As an effort to produce a comprehensive agent architecture that can utilize qualitative data to capture consumer behavior, a few years ago we decided to implement Triandis' Interpersonal Behavior (TIB) (Triandis, 1977) in our platform, Behavior Demand Model (BedDeM), by using the Repast library for agent-based modelling. TIB is chosen due to its expressiveness as a theory for human behavior and ability to calculate expected utility with its tri-level form, in a way that is compatible with how bounded rationality can be manifested in human decision-making.

BedDeM's first application was in the domain of mobility, whose main purpose is to generate daily mobility demands at the individual household level based on their modal choices for daily trips. We utilized the Swiss Household Energy Demand Survey (SHEDS) and the Mobility and Transport Microcensus (BFS, ARE, 2017) to parametrize the household profiles, build and calibrate a synthetic population (Nguyen, K. and Schumann, R., 2019a). A weekly schedule is also derived for each agent from the MTMC to provide a way to calculate all relative attributes for a trip (including purpose, distance, execution time). The agent's main purpose is to select a mode of transportation (including rail, car, bus, tram, biking, walking, others) to perform a task on its schedule.

As for the calibration of the model, the current version has already been calibrated to aggregate and disaggregate statistics of the Swiss mobility systems. In particular, it is able to reproduce the large majority of trips contained in Mobility Microcensus 2015 (BFS, ARE, 2017), carried out by the real agents to which artificial agents have been matched to.

This model has been used to explore the importance of different determinants (Nguyen, K. and Schumann, R., 2019) and charging pattern for electric vehicles (Nguyen, K. and Schumann, R., 2020).

With the envisioned extensions of the BedDeM model (see Section 3 of this Annex) and its existing functionalities, BedDeM covers, both purchase of mobility resources, as well as their usage, in two intertwined decision-making schemes.

14.4.5. Lessons learned for the co-simulation of models of the Swiss Energy system

Linking models, even in tight co-simulations, is feasible by taking a modular approach in which each model is considered in its inputs and output and their interconnections. This does not require matching modelling philosophies, internal structures, and technical aspects, which would be needed for a model integration. However, it does require precise mapping of the variables and of data structures.

In particular, a preliminary analysis of the models to be linked needs to single out the endogenous variables that appears in both models because it has to be avoided that the same real variable is given two values for the same year. An ex-ante choice has to be made about which model actually determines the value, in a sense "over-writing" the other. This makes the variable exogenous from the point of the view of the latter model.

It is important to refer models to fixed points in time, ideally corresponding to the calendar time. Thus, relevant points in time of the simulations can be mapped to each other. So, even though two models do not need to have the same granularity of temporal resolution, there is the need that their underlying representation of times allows for the identification of regular synchronization points both. This is needed to correctly adapt changes in the input data, as well as provides interruption points of one model's execution which is needed in the co-simulation approach. For example, BedDeM provides data in a sub-annual resolution (typically for representatives' weeks, one for each quarter of a year), while STEM often works with time windows of 5-10 years. This enables that BedDeM can iterate for e.g. 20 time steps, which would be equivalent of one time step of STEM. Finally, a general flexibility in treating a large range of apparently minor details greatly helps in establishing the working interface among models.

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White paper on "Redesigning policies in a bounded rationality framework"

1. The energy transition: risks and opportunities linked to bounded rational consumers

The energy transition of Switzerland requires changes in the adopted technologies and their utilization. When key decentralized decision-making is embedded in humans, the outcome may deviate from what expected by a social planner. Cognitive and emotional limits tend to narrow the choice set and the actually chosen products and solutions. Low-carbon alternatives may be dismissed already in the filtering phase and not given proper consideration during an explicit evaluation. Thus, their positive objective features and their improvements over time may not be salient: efforts to introduce them risk not to be rewarded by market success. A lock-in in high-carbon solutions may result from such dynamics.

Partial participation to the market (with only a minority percentage of the population participating in a given year to the market), coupled with the heterogeneity of consumers, produces successive waves, which can be interlinked. If, in particular, the past purchases by pioneers, the media environment and the public perception allow for inclusion of low-carbon technologies in the choice set of the next waves of purchases, a concentration on one technological direction can take place, because of a narrow set of choices. This is what happens in the baseline scenario generated by the PROBOUND project. In the private motorized mobility sector in the hands of households, battery electric vehicles (BEV) end up dominating sales. In 2041, the majority of the fleet becomes electric. At the end of the transition, the remaining 17.8% of internal combustion engines, deriving from a lack of purchase of new cars, are using carbon-neutral liquid fuels.

The narrow attention of the consumer is thus shifted to one specific (Tank-to-Wheel) zero carbon mode. This result is rooted in the above-mentioned market developments, the widening supply of electric vehicles by a more diverse set of manufacturers and a lack of new compelling models in traditional internal combustion engine models.

Bounded rational consumers can be radically dismissing high-carbon solutions, and this is clearly an opportunity for the energy transition. However, the triggering mechanisms have to cope with the "confirmation bias" and the social elaboration of information and emotional meanings and do not derive entirely from the objective features of the system. For instance, the sheer presence of charging stations may not lead to a drastic reduction of pre-purchase "range anxiety" (a typical reason to dismiss BEV entirely) unless their presence is very visible.

2. Widening the policy toolbox with policies taking bounded rationality into account?

The traditional toolbox of economics builds upon a rational consumer that reacts mainly to prices, subject to a budget constraint and given preferences. Accordingly, price signals and quantity signals (which a market converts in prices) are the main venues for policy interventions. For climate purposes, CO_2 taxes, subsidies and cap-and-trade policies have been proposed and widely evaluated since the '80s of last century. The only other family of policies that would have effects are regulations, usually in the form of a prohibition. In this context, policies addressing the informational and cognitive environment of decision-making have been dismissed as relying on a "cheap talk" that consumers would ignore.

The PROBOUND project, on a background of an even wider range of policies, has quantitatively evaluated the impacts of eight policies, targeting driving tests and other personal experiences surrounding or preceding the decision-making process, the judgmental context, the perception, the simplified information delivered by energy labels, as well as price signals (in the form of subsidies for the purchase of electric vehicles and for charging stations). The policies aims to address touchpoints of a bounded-rational process of purchase which extends over time, is triggered by objective and subjective factors, and can lead not only to purchase a new vehicle but also a new mobility resource (such as the General Abonnement travel card to public transport). Some policies draw on nudging, others are independent from it.

Within the models and the assumptions of the project, these policies have resulted in a diversified effectiveness: several of them are quite effective in the short term to boost sales of electric vehicles and to increase the use of public transport. Some of them anticipate to 2035 the year in which the fleet is composed by a majority of BEV, from the 2041 of the baseline. In 2050, they reduce the 17.2% of residual ICE vehicles of the baseline to a share within a range between 9.3% and 15.6%, depending on the policy.

This high penetration of BEV reduces CO_2 emissions. Thus, the earlier adoption reduced to total amount of emissions, created over the years. Particularly, the bounded-rational polices on EV drive trials (TT1) and financial support for charging station (FACH1) induce the highest CO_2 mitigation[66]. In these policies, on an average, annually about one million tons of CO_2 is reduced in from the transportation sector during 2024-2036 compared to the Baseline scenario, whereas the fleet's share of BEV in 2030 increase to 40% compared to 17% in the Baseline.

In summary: the policies providing price signals are effective in modifying purchases and behaviors. Non-price policies are also effective. The effectiveness of the two types of policies is in the same order of magnitude. This result is a major contribution to the debate on policies for the energy transition, and draws attention to marketing science as a source of consumer science. It is obtained quantitatively within a model, not in an experiment with people – and would probably need several of them to be qualified and confirmed.

[66] For a concise description of the designs and for their acronyms, see the Annex.

3. Individual bounded rationality provokes significant energy-system level impacts of the policies which take it into account

There is a tendency in the psychological literature on bounded rationality to concentrate on the effects to the individual behavior and welfare. The PROBOUND project, which has explored policies leveraging bounded rationality by consumers, has detected significant energy-system level impacts of adopting these policies. Within a net zero trajectory in which the system does not overshot the 2030 CO_2 target, the CO_2 mitigation deriving from these bounded-rational polices helps avoiding expensive mitigation measures in other end use sectors. For example, expensive energy conservation measures in the industrial and residential sectors are avoided. Therefore, CO_2 emissions in these sectors increase in 2030.

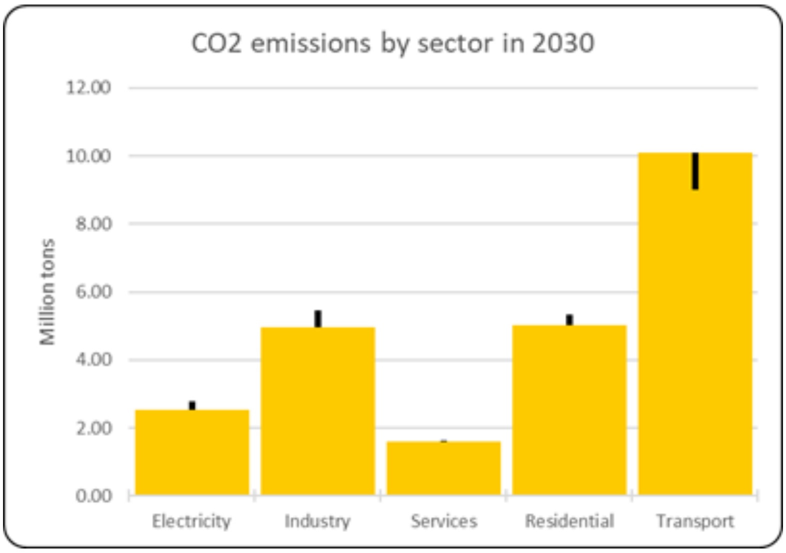

Figure 1: Annual CO_2 emission in 2030 by end use sector. The solid yellow bars show the emission level in the baseline and the black bars indicate the maximum change across various BR policy scenarios.

In the electricity sector, there are significant impacts in terms of investments in solar photovoltaics (PV) and imported electricity, because of the increase of electricity demand in the transport sector. These results represent, both from a methodological and a content point of view, a contribution to a wider future discussion.

4. The importance of specific designs of policies for their effectiveness

The parametrization of a policy is as important as the type of policy itself. The same policy can be designed in many alternative ways. In the project, we call "design" a specific parametrization of a policy, including, in certain cases, its geographical coverage, its beneficiaries, and some further details (e.g. within the policy of mandatory information at dealerships which is the content of information). The ranked effectiveness of all designs exhibit "alternation", i.e. a design of a first policy can be superior to a design of a second policy but inferior to another design of the second policy.
For instance, let's look at the average market shares of BEV in sales for 2023-2027 and compare the policy centered on energy labelling and the policy centered on the "information bubbles" in the media environment. The former has two designs, tested quantitatively in PROBOUND: LAB1 and LAB2. For the sake of the argument, let's ignore in what they are different. The second policy is articulated in four designs: BUB1, BUB2, BUB3, BUB4. The designs of the two policies alternate: LAB1 produces a lower market share than BUB2 but higher than BUB3. LAB2 produces a market share lower than all BUB. In this case, the percentage differences are not particularly large. Still, from a conceptual point of view, it's remarkable that the discussions on policies (and their relative advantages and disadvantages) need to keep into consideration a fine-tune of the policy design, when we move from philosophical fundamental differences (and the mapping of which stakeholder would be activated, which tend to be the same for all designs of the same policy) into a discussion about their effectiveness.
On a more general level, redesigning policies under a bounded rationality framework would probably involve recognizing that people may not pay attention to the policy itself and that too weak a parametrization of the policy may remain below a threshold of activation. Bounded rationality calls for simple and clear policy messages and designs.

Design	BEV share in sales (2023-2027) ranked from highest to lowest
TT1	57.8%
FACH1	53.7%
INDE1	48.2%
TCO1	47.8%
INDE3	47.3%
VIS2	46.8%
BUB2	46.3%
INDE2	46.1%
BUB1	45.7%
LAB1	45.7%
BUB4	45.6%
BUB3	45.2%
VIS1	45.1%
SLOCH3	39.9%
SLOCH4	39.7%
SLOCH2	39.0%
SLOCH1	38.9%
FACH2	38.9%
TT2	38.6%
LAB2	38.3%
TT3	29.2%
Baseline	36.0%

Table 1- Share of battery electric vehicles in sales. The designs are characherized by an acronym whose letters reflect the policy and the number the design, concisely described in the Annex.

5. A cautionary approach to new policies

The PROBOUND project has produced a vast array of quantitative results, indicating the effects of policies as for the yearly sales, the fleet, the modal choices (thus the passenger km and vehicle km), the CO_2 emissions and costs. These results are rooted in the models, their structure and assumptions, inputs and parameters, both at national level and at agent level. This would be true for any similar model. In our case, we tightly co-simulate two models, so the degree of complexity is increased.

Within these limits, one might indicate the following priority policies:

1. the provision of opportunities for driving trials of BEV;
2. the support to fast charging;
3. mandatory information at dealerships;
4. a communication campaign raising the importance in decision-making of energy labels.

In the first year of introduction, the most successful policies turned out to be the following:

1. the penetration of “information bubbles”, where a conversation about pros and cons of different technologies takes place,
2. increasing the visibility of fast charging stations through road signs.

The fact that, within the models, most policies leveraging bounded rationality are somewhat effective, should be balanced with qualitative, out-of-model, considerations. In the models, the policy to provide large opportunities to personally drive an electric vehicle as test for a few months turned out to be the most effective way to increase sales. In reality, much depends e.g. on whom would take part in such testing: only already convinced people or also skeptics that would revised several negative judgements? Many details of the setting would probably exert an impact: dealer-centric or more neutral with respect to brands; driving or being a passenger; alone or with someone; the accompanying people and kind of explanation (by an interested seller or a veteran of electric drives in all conditions); the duration of the test (which in practical conditions may be much shorter than what used in the models). Full details of the design, that would matter to a bounded rational consumer, cannot or could not be implemented in PROBOUND models.

In a broader assessment, one would need to take into consideration:

- the cost of introducing the policy, which is traditionally negligible for several bounded-rationality touchpoints but whose evaluation has not been part of PROBOUND;
- its public acceptance;
- the cost of the effects of the policies (a very effective policies raising the purchase of EV has been for instance demonstrated as expensive in a logics of net zero trajectories, displacing activities in other parts of the energy system);
- the degree of integration from different stakeholders that the policy may require;
- its distributional impact;
- its synergies or trade-offs with other policies, also across sectors, as we have shown that due to the reductions of emissions in the mobility sector, particular (needed) changes in the building sector had been delayed.

On a more general level, widening the policy toolbox increases the complexity of selecting the policy but also allows to activate processes even when other policies may have encountered problems in approval and implementation. Conversely, additional research efforts may be directed to designs to be applied together.

In terms of policy targets, it should be underlined that the baseline already achieves, in absence of policies, the number of battery electric vehicles indicated in SFOE “Scenario framework for electricity network planning”[67], issued on 23 Nov. 2022. In particular, the baseline generates 2’634’566 EVs in 2040, nicely between Scenario 2 (2’520’000), Scenario 1 (2'940'000) and Scenario 3 (3 230 000). For 2030, the PROBOUND baseline indicates 854’179 EV, which is slightly below all scenarios (870’000 in

[67] https://www.bfe.admin.ch/bfe/en/home/supply/electricity-supply/electricity-networks/grid-development-electricity-grid-strategy/scenario-framework.html and in particular p. 5 of https://www.bfe.admin.ch/bfe/en/home/versorgung/stromversorgung/stromnetze/netzentwicklung-strategie-stromnetze/szenariorahmen.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZGUvcHVibGljYX/Rpb24vZG93bmxvYWQvMTA3NDk=.html

Scenario 3, 930’000 in Scenario 1 and 980’000 in Scenario 2). In the baseline, a value of 967’998 is achieved in 2031[68].

Accordingly, the policies examined by PROBOUND are not necessary to achieve those values. However, their implementation, according to the models, would significantly anticipate those values and then reach higher values across the trajectory. If the precautionary principle is applied in this part of the climate policy (so that earlier fall in emissions is positively evaluated), then such policies could be subject to further evaluation and plans for implementation might be contingently elaborated.

These policies are particularly important if the current real-world trend is not considered to be in line with net zero goal, because they act as an insurance against undesirable developments (e.g., lack of action in other sectors, unavailability of price-competitive climate-neutral fuels, etc.) by accelerating the electrification of passenger transport.

Policymakers aiming at fast decarbonization of the mobility sector should take into consideration the possibility of investigating policies leveraging bounded rationality and assess their interest, in part through models like the ones underpinning the PROBOUND project, in part through complementary methods (such as experiments and public acceptance studies).

The results of PROBOUND can be, *mutatis mutandis*, utilized for the overall sustainability of the mobility sector and all other energy sectors where individual decision-making is characterized by bounded rationality.

[68] The policy implication is that, while TSOs and DSOs may in principle consider the three scenarios as a high, a low, and an intermediate scenario, the baseline would suggest rather a rapid temporal sequence of earlier the lowest, then the intermediate, then the highest.

Annex to "Redesigning policies in a bounded rationality framework"

Policies and designs	
Shifting contents and exposure to "information bubbles"	
BUB1	Enhanced positive messages in the neutral oriented media
BUB2	Enhanced positive messages in the positive oriented media
BUB3	Minor but new presence of positive opinions in the negatively oriented media
BUB4	Strengthening exposure to positively oriented media
Support for Fast charging	
FACH1	Financial support; leading to more charging in reality
FACH2	National standards and financial support; leading to higher Opinions on the topics
Support for Slow charging	
SLOCH1	Charging opportunity at the home of tenants (50% of eligible population)
SLOCH2	Charging opportunity at work (50% of eligible population)
SLOCH3	Charging opportunity at shopping (50% of eligible population)
SLOCH4	Charging opportunity at the home of homeowners (50% of eligible population)
Charging stations visibility from the road	
VIS1	Visibility of DC fast charging stations from 2 km
VIS2	Visibility of DC fast charging stations from 5 km
Energy label policies	
LAB1	A successful communication campaign aimed at raising salience of the energy label
LAB2	Energy label "A" is reserved for zero direct emission vehicles
Mandatory information at dealerships	
INDE1	An ordered list of emissions of all vehicles of the brand (from lowest to highest) is provided to prospective customers and signed by them
INDE2	Map of charging stations
INDE3	Automatic subscription to all charging networks & payment systems
Drive tests	
TT1	EV (nationally scattered) trials for three years
TT2	Micro-mobility vehicles nationally scattered trials for three years
TT3.	GA (nationally scattered) trials for three years
Total cost of ownership	
TCO1	Subsidy to the prices of EV (costing less or equal to 23 000 CHF) by a 7 000 CHF reduction