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Optimale Struktur von dezentralen und zentralen Technologien im Systemverbund – Intelligente dezentrale Energiesysteme

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- Schlussbericht -

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Infolge der Energiewende wird das deutsche Energiesystem durch die variable räumliche Verteilung der erneuerbaren Energieressourcen, die Heterogenität der Akteure und die Vielfalt an Technologien und Politiken zunehmend komplexer und dezentralisierter. Dezentralisierung bedeutet, dass der Energiebedarf durch eine Vielzahl kleinerer Einheiten gedeckt wird, die sich innerhalb des Energiesystems am Ort des Verbrauchs oder nahe dazu befinden. Das Vorhaben zielt auf die verbesserte Abbildung der Akteure sowohl auf der Versorger- als auch auf der Verbraucherseite in der Modellierung. Zur Analyse der Dezentralisierungstendenzen wird ein methodischer Ansatz entwickelt, der es erlaubt, die unterschiedlichen Entscheidungssituationen der verschiedenen Akteure in den verschiedenen Sektoren und gleichzeitig die Auswirkungen auf das Gesamtsystem zu erfassen. So wird das gesamte deutsche Energiesystem anhand separater Sektormodelle erfasst. Die sektoralen Modelle werden über Kopplungsmechanismen zur Abbildung des gesamten Energiesystems zusammengeführt. Die Kombination der gekoppelten Sektormodelle wird als TIMES-Akteursmodell (TAM) bezeichnet. Insgesamt zeigt die Anwendung von TAM, dass die Energiewende zu mehr Dezentralisierung im Energiesystem durch mehr Eigenerzeugung in allen Nachfragesektoren führen wird. In Abhängigkeit des Systementwicklungspfades ist der letztendliche Grad der Dezentralisierung jedoch unterschiedlich. Die Nachfragesektoren werden jedoch nicht in der Lage sein, ihren Energiebedarf autonom zu decken, und das zentrale Energiesystem wird weiterhin vor allem im Hinblick auf die Bereitstellung von Strom, Fernwärme und Wasserstoff von Bedeutung sein.

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The German energy system is increasingly becoming more diverse and decentralised through the variable spatial distribution of the renewable energy resources, heterogeneity of actors and the variety of technologies and policies. Decentralisation is understood as fulfilling the energy demand by small, multiple generation units which are located at the consumption side of the energy system. Current gaps in decision support tools are addressed aimed at improving the representation of both supplier and consumer actors in energy system modelling. To analyse the decentralisation tendencies, a methodological approach is developed which allows the different decision situations of the diverse actors in different sectors to be modelled while recording the effects on the development of the whole system. Thus, the overall German energy system is investigated through separate sector models. The sectoral models are then combined via coupling mechanisms to represent the entire energy system. The combination of the coupled sector models is named TIMES Actors Model (TAM). Overall, TAM demonstrates that the energy transition encourages the current energy system towards more decentralisation through self-generation in all demand sectors. However, depending on the system development pathway, the ultimate degree of decentralisation differs. However, the demand sectors will not be able to fulfil their energy requirements autonomously and the central energy system will remain significant especially in terms of electricity, district heating and hydrogen provision.

19. keywords

Systems analysis, Energy system, Decentralisation, TIMES, Model coupling, Actors behaviour

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B2DS	Below 2 degrees climate change	MILP	Mixed Integer Linear Programming
BEVs	Battery electric vehicles	MOP	Mobilitätspanel
BTKM	Billion tonne kilometers	MW	Megawatts
BPKM	Billion passenger kilometers	N2O	Di-Nitrogen Oxide
CAPEX	Capital expenditures	NEP	Netzentwicklungsplan
CA-TIMES	TIMES Canada	O&M	Operation and Maintenance
CCS	Carbon capture and storage	OPEX	Operation expenditures
CCU	Carbon capture and utilization (use)	PHEVs	Plug-in hybrid electric vehicles
CFT	Carbon-free targets scenario	PIB	Public Investment Budget
CH4	Methane	PJ	Petajouls
CHP	Combined heat and power generation	PKM	Passenger Kilometers
CNG	Compressed Natural Gas	PV	Photovoltaic
CO2	Carbon Dioxide	RCA	Reserve Capacity Scenario
CO2-eq.	Carbion Dioxide equivalent emissions	REF	Reference Scenario
COP21	2015 United Nations Climate Change Conference	REFYR	Reference Year
CSP	Concentrated solar power	SFH	Single Family House
CTX	Carbon tax scenario	TAM	TIMES Actor Model
DE	Germany	TECHS	Technologies
DSM	Demand side management	TIB	Travel Investment Budget
ETS	Emission Trading System	TIMES	The Integrated MARKAL-EFOM SYSTEM
ETSAP	Energy Technology Systems Analysis Programme	TIMES-D	TIMES-Germany
ETSAP-TIAM	ETSAP TIMES Integrated Assessment Model	TIMES-DK	TIMES-Denmark
EU	European Union	TIMES-EU	TIMES-Europe
FCEVs	fuel-cell electric vehicles	TJ	Terajouls
FiT	Feed-in tariffs	TMB	Travel Money Budget
GDP	Gross domestic production	TTB	Travel Time Budget
GHD	Gewerbe, Handel, Dienstleistungen	UK	United Kingdom
GHG	Greenhouse gases	UN	United Nations
GJ	Gigajouls		
GW	Gigawatts		
IEA	International Energy Agency		
IG	Income Group		
IIS	Iron and Steel Industry		
JRC	Joint Research Centre		
KWK	Kraft-Wärme-Kopplung		
LEAP	Long-range Energy Alternatives Planning		
LPG	Liquified Petroleum Gas		
MARR	Minimum Accepted Rate of Return		
MFH	Multiple Family House		

Zusammenfassung

Infolge der Energiewende wird das deutsche Energiesystem durch die variable räumliche Verteilung der erneuerbaren Energieressourcen, die Heterogenität der Akteure und die Vielfalt an Technologien und Politiken zunehmend komplexer und dezentralisierter. Dezentralisierung bedeutet, dass der Energiebedarf durch eine Vielzahl kleinerer Einheiten gedeckt wird, die sich innerhalb des Energiesystems am Ort des Verbrauchs oder nahe dazu befinden. Diese Diversität bietet eine gewisse Flexibilität und erleichtert die aktive Beteiligung von Energieerzeugern und -verbrauchern, erhöht aber gleichzeitig die Komplexität, die ehrgeizigen Ziele der Energiewende kosteneffizient erreichen zu können. Dies zeigt die Herausforderung für die Zielerreichung, insbesondere für ein solch komplexes System, das aus verschiedenen Akteuren in unterschiedlichen Umfeldern besteht, die zwischen alternativen Technologien wählen können.

Modellgestützte Analysen werden häufig verwendet, um die Auswirkungen alternativer Energiepolitiken zu bewerten, um den politischen Entscheidungsprozess effektiv zu unterstützen, verschiedene Wege für die Energiewende zu analysieren und mögliche Auswirkungen solcher Entwicklungen abzuschätzen. Derzeit genutzte Energiemodelle berücksichtigen jedoch überwiegend nicht ausreichend die Herausforderungen, die sich aus den Investitionsfähigkeiten und Erwartungen der verschiedenen Akteure ergeben. Diese werden z. B. durch die sozio-ökonomischen Merkmale auf der Nachfrageseite und die jeweiligen Wechselwirkungen bestimmt.

Das Vorhaben zielt auf die verbesserte Abbildung der Akteure sowohl auf der Versorger- als auch auf der Verbraucherseite in der Modellierung. Zur Analyse der Dezentralisierungstendenzen wird ein methodischer Ansatz entwickelt, der es erlaubt, die unterschiedlichen Entscheidungssituationen der verschiedenen Akteure in den verschiedenen Sektoren und gleichzeitig die Auswirkungen auf das Gesamtsystem zu erfassen. So wird das gesamte deutsche Energiesystem anhand separater Sektormodelle erfasst. Die sektoralen Modelle werden über Kopplungsmechanismen zur Abbildung des gesamten Energiesystems zusammengeführt. Die Kombination der gekoppelten Sektormodelle wird als TIMES-Akteursmodell (TAM) bezeichnet.

Um die Auswirkungen auf die Dezentralisierung des deutschen Energiesystems und die Ausgestaltung der dafür notwendigen Rahmenbedingungen zu ermitteln, werden mit TAM drei Szenarien analysiert: „Reference" (REF), „Carbon tax" (CTX) und „Carbon-free targets" (CFT) Szenario. Die Ergebnisse ermöglichen Einblicke in das Akteursverhalten, um Politikmaßnahmen unter Berücksichtigung des Akteursverhaltens im Energiesystem spezifisch ausgestalten zu können. Die Szenarienanalyse zeigt, dass typischer Weise bei der Energieplanung verwendete aggregierte Modelle sowohl den Gesamtverbrauch überschätzen als auch die Gesamtemissio-

nen unterschätzen. Für die Industrie ist eine tiefgreifende Dekarbonisierung ein kostenintensiver Prozess, der individuell zugeschnittene Strategien für verschiedene Industriezweige und ihre Akteure erfordert, da sie jeweils mit spezifischen Herausforderungen konfrontiert sind. Es ist zwar ein erhöhtes Maß an Dezentralisierung in der Industrie zu erwarten und für die Dekarbonisierung notwendig. Jedoch wird dieses Niveau bei einer aggregierten Modellierung weitgehend überschätzt. Im Haushaltssektor sind kurz- bis mittelfristig Investitionen erforderlich, die darauf auszurichten sind, die Eigenversorgung zu stärken, vor allem im Mietwohnungsbau, besonders in städtischen Mehrfamilienhäusern. Finanzielle und gesetzgeberische Unterstützung für die Reduktion der Nachfrage durch Gebäudesanierung und die Marktdurchdringung von Wärmepumpen und Solarthermieanlagen ergänzen dies. Der Personenverkehrssektor bringt die höchsten marginalen Kosten bei der Emissionsminderung mit sich, nicht nur wegen der kostspieligen Infrastruktur und der Flottenerneuerung. Hier geht auch das Entscheidungsverhalten der Verbraucher ein, das immaterielle Kosten, wie z. B. die Reisezeit, einschließt, was sich negativ auf die Nutzung des zum Teil effizienteren ÖPNV auswirkt. Daher sind einfache Preisaufschläge für den Verbrauch fossiler Brennstoffe unzureichend, um ihn in Richtung Dekarbonisierung zu lenken. Im Energiebereitstellungssektor könnte jede Akteursgruppe mit den jeweiligen spezifischen Finanzierungsbedingungen in jeder modellierten Region in Deutschland in ein bestimmtes Technologieportfolio investieren, so dass das gesamte Energiesystem die Ziele der Energiewende zu geringstmöglichen Kosten erreicht. Die Finanzinstitutionen könnten ihren Fokus auf die Onshore-Windenergie legen, insbesondere im Norden. Die Versorgungsunternehmen sollten sich auf das Potenzial der Offshore-Windenergie konzentrieren und ausreichende Netz- und Reservekapazitäten sicherstellen. Die Energiegenossenschaften könnten ihr verfügbares Kapital für Investitionen in die Freiflächen-PV, besonders in Süddeutschland, nutzen.

Insgesamt zeigt die Anwendung von TAM, dass die Energiewende zu mehr Dezentralisierung im Energiesystem durch mehr Eigenerzeugung in allen Nachfragesektoren führen wird. In Abhängigkeit des Systementwicklungspfades ist der letztendliche Grad der Dezentralisierung jedoch unterschiedlich. Die Nachfragesektoren werden jedoch nicht in der Lage sein, ihren Energiebedarf autonom zu decken, und das zentrale Energiesystem wird weiterhin vor allem im Hinblick auf die Bereitstellung von Strom, Fernwärme und Wasserstoff von Bedeutung sein.

Der neu entwickelte Modellansatz, das TIMES-Akteursmodell (TAM), erlaubt es, das Akteursverhalten mit inter- und intrasektoralen Wechselwirkungen sowie Rückkopplungen im Energiesystem zu erfassen und detailliert zu bewerten. Auf die Teilsektoren abgestimmte politische Maßnahmen sollten gezielt implementiert werden, um einen integrierten Gesamtpfad für eine kosteneffiziente Erreichung der Ziele der Energiewende besser zu gewährleisten.

Summary

The German energy system is increasingly becoming more diverse and decentralised through the variable spatial distribution of the renewable energy resources, heterogeneity of actors and the variety of technologies and policies. Decentralisation is understood as fulfilling the energy demand by small, multiple generation units which are located at the consumption side of the energy system. The diversities offer flexibility and facilitate the active participation of energy producers and consumers while increasing the complexity of ensuring that the ambitious goals of the energy transition are met in a cost-effective manner. Therefore, the German energy transition targets are quite challenging, particularly for such a complex system consisting of diverse actors located in different environments facing several alternative generation and end-use technologies.

Model-based analyses are commonly applied to assess the impact of alternative energy policies to inform an effective policy-making process, determine different pathways for the energy transition and analyse possible impacts of such developments. However, energy models currently used to support and assess energy and climate policies at national and EU level do not fully represent and integrate the challenges arising from the economic investment abilities and expectations of the various actors determined by, for example, the socio-economic characteristics of the demand-side and the respective interactions.

Current gaps in decision support tools are addressed aimed at improving the representation of both supplier and consumer actors in energy system modelling. To analyse the decentralisation tendencies, a methodological approach is developed which allows the different decision situations of the diverse actors in different sectors to be modelled while recording the effects on the development of the whole system. Thus, the overall German energy system is investigated through separate sector models. The sectoral models are then combined via coupling mechanisms to represent the entire energy system. The combination of the coupled sector models is named TIMES Actors Model (TAM).

TAM is used to analyse three policy scenarios and their effect on the optimal degree of decentralisation in the German energy system: the reference (REF), high carbon taxes (CTX) and carbon-free targets (CFT) scenarios. Results provide insights into behaviour of specific actor groups and allow policies and measures to be specifically tailored, enabling a better understanding of the investment and consumption behaviour of these different players in the energy sector. The application of TAM has shown that the common aggregated method applied towards energy planning can overestimate overall consumption as well as underestimate the

overall emissions. A deep decarbonisation for the industrial sector is a cost-intensive process that will require individually tailored policies for different industrial branches and their actors as they each face unique challenges and thus react differently to carbon taxes. While it can be observed that an increased degree of decentralisation in industry can be expected, this level is largely overestimated in the aggregated method. The household sector will require investments in the short to medium term aimed at ensuring participation and harnessing the potential of the rental sector, particularly in urban multi-family homes, where the greatest demand for heating and water heating resides. Financial and legislative support targeting building insulation to reduce demand and support heat pumps and solar thermal technologies to make these more attractive will be required. The passenger transport sector is the most expensive sector to decarbonise not only due to costly infrastructure and fleet extensions but also due to consumer's decision making behaviour which includes intangible costs such as travel time, adversely affecting the use of more efficient public transport means. Therefore, high disincentives for consuming fossil fuels are insufficient and legislative support will be required for this sector to steer it towards decarbonisation. Each actor group within the energy supply sector, with its unique financial characteristics, should invest in a particular technology portfolio in each modelled region within Germany so that the overall energy system meets the energy transition goals at least system costs under different frameworks. For instance, financial institutions should place their main focus on onshore wind, particularly in the north, while it would be more cost-effective from a system perspective if utilities maximised the potential of offshore wind and ensure the availability of enough grid reserve capacity. The overall system can benefit more if citizens, in the form of energy cooperatives, allocate their available capital for investments in ground-mounted PV, especially in the southern part of Germany.

Overall, TAM demonstrates that the energy transition encourages the current energy system towards more decentralisation through self-generation in all demand sectors. However, depending on the system development pathway, the ultimate degree of decentralisation differs. However, the demand sectors will not be able to fulfil their energy requirements autonomously and the central energy system will remain significant especially in terms of electricity, district heating and hydrogen provision.

The newly developed model approach is particularly for detecting inter- and intra-sectoral interactions as well as feedback within the energy system and to evaluate them in detail. The insights derived through this methodology has revealed specific sub-sectors to be targeted with policy measures so as to better ensure an overall pathway towards a cost-effective investment and consumption strategy to achieve the objectives of the energy transition.

Das Wichtigste in Kürze

Das auf der COP21 erzielte Pariser Klimaabkommen hat die Notwendigkeit eines baldigen Übergangs zu einer CO_2-armen Wirtschaft bekräftigt. Infolge der Energiewende wird das deutsche Energiesystem durch die variable räumliche Verteilung der erneuerbaren Energieressourcen, die Heterogenität der Akteure und die Vielfalt an Technologien und Politiken zunehmend komplexer und dezentralisierter. Diese Diversität bietet eine gewisse Flexibilität und erleichtert die aktive Beteiligung von Energieerzeugern und -verbrauchern, erhöht aber gleichzeitig die Komplexität der Gewährleistung, dass die ehrgeizigen Ziele der Energiewende kosteneffizient erreicht werden. Dies zeigt die Herausforderung bei der Erreichung der Ziele der Energiewende, insbesondere für ein solch komplexes System, das aus verschiedenen Akteuren in unterschiedlichen Umfeldern besteht, die sich zwischen alternativen Erzeugungs- und Nutzungstechnologien entscheiden können. Die Energiewende sollte zum einen auch keine negativen finanziellen Auswirkungen auf die Akteure haben und auch nicht die Energiebedarfsdeckung beeinträchtigen. Andererseits könnten die unterschiedlichen Akteurscharakteristika gleichzeitig dem System bei der Energiewende helfen, indem verschiedene Akteure auf der Basis ihres Erzeugungspotenzials zu einer kosteneffizienten Ausgestaltung beitragen können.

Dezentralisierung bedeutet, dass der Energiebedarf durch eine Vielzahl kleinerer Einheiten gedeckt wird, die sich innerhalb des Energiesystems am Ort des Verbrauchs oder nahe dazu befinden. Die zu erwartende Dezentralisierung der Energieerzeugung macht die Bereitstellung einer zuverlässigen Stromversorgung komplexer, so dass eine umfassende Analyse des Energiesystems zur Abschätzung der Auswirkungen der zu erwartenden Entwicklungen unabdingbar ist. Neben den alten und neuen Akteuren im Versorgungssektor stehen daher die Energieverbraucher im Mittelpunkt der Energiewende und spielen eine entscheidende Rolle, um die Effizienz bei der Energienutzung zu steigern oder um „Prosumer“ bzw. „Prosumenten“ zu sein und damit die künftige Struktur des Energiesystems zu gestalten. Technologische Veränderungen durch Investitionen in CO_2-arme Technologien werden für die Erreichung der Dekarbonisierung von entscheidender Bedeutung sein, aber die sozialen, wirtschaftlichen und verhaltensbezogenen Aspekte sind ebenso wichtig, um die Betriebs- und Investitionsentscheidungen der Verbraucher analysieren und ggf. beeinflussen zu können.

Die Ausgestaltung der Energie- und Klimapolitik wird seit Langem durch die Entwicklung und Anwendung von Energie-Umwelt-Ökonomie-Technik-(E4)-Modellen unterstützt, in dem diese die ökologischen, ökonomischen und technologischen Dimensionen des integrierten Energiesystems abbilden. Obwohl gängige Modelle zur Optimierung von Energiesystemen mit hoher Technologiefundierung leistungsstarke Instrumente zur Analyse kostengünstiger Dekarbonisierungspfade sind, stellen die meisten Modelle Energiesysteme auf der Grundlage von wenigen durchschnittlichen Akteuren dar, die jeweils große Gruppen von Verbrauchern oder Produzenten repräsentieren. Sie berücksichtigen daher nicht die einzigartigen wirtschaftlichen, technischen und rationalen Verhaltensmerkmale der verschiedenen Akteure, was folglich zu ungenauen Ergebnissen und damit zu unrealistischen Politikempfehlungen führen kann. Daher sind Modelle mit dieser typischen Struktur nicht in der Lage, Fragen zur Dezentralisierung des Energiesystems adäquat zu behandeln. Investitionen in dezentralisierte Technologien werden überwiegend von den unterschiedlichen sozioökonomischen und finanziellen Merkmalen der Akteure beeinflusst. Daher ist es notwendig, die Abbildung der Akteure zu verbessern, um sowohl Aspekte der Politikgestaltung als auch Transformationspfade eines langfristigen Übergangs zu einem Treibhausgas-neutralen Energiesystem analysieren zu können.

Um Fragen der Dezentralisierung in die Energiesystemplanung besser einzubinden und eine bessere Unterstützung der politischen Entscheidungsfindung zu modellieren, ist das Konzept des vorliegenden Vorhabens darauf ausgerichtet, aktuelle Lücken in den Entscheidungsunterstützungssystemen zu erkennen und die Abbildung der Akteure sowohl auf der Versorger- als auch auf der Verbraucherseite in der Energiesystemmodellierung zu verbessern. Ziel dieses Vorhabens ist die Analyse des optimalen Anteils zentralisierter und dezentralisierter Energietechnologien im gesamten deutschen Energiesystem. Um den Zielsetzungen dieser Studie gerecht zu werden, werden methodische Erweiterungen durchgeführt, um zu einer verbesserten Darstellung der Vielzahl heterogener Akteure zu gelangen.

Methode

Die Faktoren werden in dem im Rahmen dieses Vorhabens neu entwickelten TIMES-Akteursmodell (TAM) berücksichtigt, das eine verbesserte Darstellung von finanziellen und sozio-ökonomischen Merkmalen heterogener Akteursgruppen auf der Versorgungs- und der Verbraucherseite des Energiesystems unter Berücksichtigung ihrer spezifischen Betriebs- und Investitionsentscheidungen erlaubt. Zur Analyse der Dezentralisierungstendenzen wird zudem ein methodischer Ansatz entwickelt, der es erlaubt, die unterschiedlichen Entscheidungssituationen der verschiedenen Akteure in den verschiedenen Sektoren und gleichzeitig die Auswirkungen auf die Entwicklung des Gesamtsystems zu erfassen. So wird das gesamte deutsche Energiesystem anhand separater Sektormodelle untersucht. Die sektoralen Modelle werden dann über Kopplungsmechanismen zur Abbildung des gesamten Energiesystems zusammengeführt. Die Kombination der gekoppelten Sektormodelle wird unter TAM zusammengeführt.

Der erste Schritt zur Berücksichtigung von Aspekten der Dezentralisierung in Energiesystemmodellen besteht in der Disaggregierung der Akteure, die bei der Energiewende eine Rolle spielen. Dann werden die heterogenen finanziellen und sozio-ökonomischen Merkmale der Akteure sowohl auf der Versorgungs- als auch der Verbraucherseite betrachtet. Hierzu werden die finanziellen Rahmenbedingungen der Akteure in der Industrie, bei den ÖPNV-Dienstleistern, bei der Energiebereitstellung und bei den Haushalten innerhalb von sieben Einkommensgruppen im Modell abgebildet. Alle Sektoren sind auf die Basisjahre 2013 und 2015 kalibriert, der Modellierungszeitraum erstreckt sich bis zum Jahr 2060. Die Stützjahre innerhalb des Modellierungszeitraumes (2013, 2015, 2020, 2025, …, 2050, 2055 und 2060) werden auf Jahresbasis beschrieben, während die räumliche Auflösung des Modells auf einer nationalen Skala erfolgt, die ganz Deutschland abdeckt, mit Ausnahme des Versorgungssektors, der Deutschland in vier Regionen aufteilt. Andere Verbraucher wie die Landwirtschaft, der Handel oder der Güterverkehr werden in dem für TIMES-Modelle traditionellen Modellansatz vereinfacht dargestellt, um ein vollständiges Bild des gesamten deutschen Energiesystems zu erhalten. Das TAM-Modell ist zudem in der Lage, die Klimagase CO_2, CH_4 und N_2O mit zu analysieren.

Jeder Sektor wird auf der Grundlage spezifischer Eigenheiten charakterisiert. So zeichnen sich beispielsweise die Unternehmen in der deutschen Industrie durch eine große Anzahl unterschiedlicher Akteure und damit durch unterschiedliche Entscheidungssituationen aus. Bezüglich der Produktionsmenge große Unternehmen haben andere Anforderungen und Rahmenbedingungen als diesbezüglich kleinere Unternehmen. Daher werden im TAM-Modell die verschiedenen Akteure in der Industrie nach Industriezweigen in verschiedene "Akteursgruppen" nach Unternehmensgröße und Produktionsweg disaggregiert. Zudem wird auf der Grundlage von Daten, die für einzelne Produktionsbetriebe erhoben wurden, eine tiefere technologische Darstellung (durch Aufschlüsselung der Produktionsprozesse) eingeführt. Darüber hinaus wird das Investitionsportfolio durch die Umsetzung von Optionen für technologische Nachrüstungen für Basisprozesse, beste verfügbare Technologien, innovative Technologien mit hohem Dekarbonisierungspotenzial (einschließlich industriespezifischer Technologien und Technologien zur CO_2-Abscheidung und -Speicherung) und Technologien zur Eigenerzeugung von Strom, Wärme, Dampf und Wasserstoff erweitert. Zur weiteren Charakterisierung der Akteursgruppen wird auch die unterschiedliche Höhe der Strom- und Gaspreise in Abhängigkeit der Höhe des Strom- und Gasverbrauchs berücksichtigt.

Die Heterogenität der Akteure im Haushaltssektor ergibt sich zum Beispiel durch die sozio-ökonomischen Merkmale, den Status quo des Gebäudetyps, die Urbanisierung, den Zugang zu verschiedenen Endnutzungstechnologien oder die Vielfalt der Entscheidungssituationen.

Diese Disaggregierung beschreibt besser das Investitionsverhalten der Haushalte in erneuerbare Technologien oder energieeffiziente Geräte und energetische Nachrüstungen. Die Investitionsentscheidungen sind für jedes definierte Profil mit Budgetbeschränkungen verbunden, die auf den verfügbaren Ersparnissen und den typischen Ausgaben für Energie nutzende Geräte sowie für Energie bezogene Gebäudesanierungen für jede Einkommensgruppe basieren.

Um die Realitätsnähe der Nutzung und der Investitionsentscheidungen von Akteursgruppen im Personenverkehr zu erhöhen, werden auch hierzu im TAM-Modell methodische Verbesserungen umgesetzt. So wird die Verkehrsnachfrage nach Fahrtdauer und Ort disaggregiert und den verschiedenen Einkommensgruppen (d. h. den Entscheidern, die die verschiedenen Haushalte sind) zugeordnet. Neben den Energieträgern nutzen die Verkehrstechnologien auch Geld und Zeit als Güter. Als Ergebnis werden das Reisegeldbudget (Travel Money Budget – TMB), das Gesamtinvestitionsbudget (Travel Investment Budget – TIB) und das Reisezeitbudget (Travel Time Budget – TTB) als zusätzliche Güter über die verschiedenen Einkommensgruppen hinweg eingeführt. Diese Güter ermöglichen es dem Modell, aus dem zur Verfügung stehenden Portfolio das Verkehrsmittel zu wählen, das die Nachfrage unter Berücksichtigung all dieser Aspekte am besten befriedigen kann. Damit ermöglicht es das Modell, auch die Verlagerung auf alternative Verkehrsmittel zur Befriedigung der Verkehrsnachfrage abzubilden, z. B. die Nutzung öffentlicher Verkehrsmittel anstelle des privaten Pkw für die jeweilige heterogene Haushaltsgruppe. Das Investitionsbudget der öffentlichen Hand (Public Investment Budget – PIB) wird ebenfalls in das Modell eingeführt. Den Akteuren des öffentlichen Verkehrs wird damit erlaubt, in neue Technologien zu investieren und die Infrastruktur auszubauen, sofern die Investitionen geringer sind als ihr verfügbares Budget. Darüber hinaus könnten sich sowohl die Akteursgruppen auf der Haushaltsseite als auch auf der Seite der Verkehrsdienstleister dazu entschließen, auf der Grundlage des verfügbaren Budgets in eine auf erneuerbaren Energien basierende dezentrale Eigenerzeugung zu investieren.

Einer der wichtigsten Faktoren für die Dekarbonisierung der Energiebereitstellung ist die räumlich ungleiche Verteilung des Angebotspotenzials erneuerbarer Energien sowie der Stromnachfrage und die damit verbundene Notwendigkeit eines weitreichenden Stromtransportes. Darüber hinaus gibt es auch verschiedene Akteure im Versorgungssektor, die sich unterschiedlichen Investitionsbewertungen, Renditeerwartungen sowie Budgetrestriktionen und damit Technologieentscheidungen gegenüber sehen, was die Heterogenität dieses Sektors noch verstärkt. Die für die Abbildung des Versorgungssektors mit dem TAM-Modell durchgeführten methodischen Verbesserungen umfassen vier Hauptschritte: 1) die Investoren in öffentliche Strom- und Wärmeerzeugungstechnologien werden in drei Hauptakteursgruppen disaggregiert, nämlich Versorgungsunternehmen, institutionelle Investoren und aus Bürger-Energiegenossenschaften; 2) die spezifischen Budgetrestriktionen der Akteure werden als einschränkender Faktor für Investitionsentscheidungen in das Modell eingeführt; 3) es erfolgt die regionale Aufteilung des deutschen Versorgungssektors in vier Regionen; 4) Netzaspekte werden in das Modell über die Regionen hinweg integriert. Damit wird das heterogene Investitionsverhalten der Akteure im Hinblick auf die Dezentralisierung in verschiedenen Regionen innerhalb Deutschlands erfasst und bei der Gestaltung von Politikinstrumenten, die auf die Dekarbonisierung des deutschen Versorgungssektors abzielen, hinsichtlich einer Optimierung weiter berücksichtigt. Der übrige Energiebereitstellungssektor, d. h. Energieträgergewinnung, -verarbeitung und -transport, wird ebenfalls modelliert, allerdings in aggregierter Form, wie z. B. die Biomasse- und Biogaserzeugung aus Energiepflanzen, die Raffinerien oder die Kohleverarbeitung usw.

Modellkopplung

Um ein vollständiges Bild des integrierten Energiesystems zu erhalten - d. h. unter Berücksichtigung der Wechselwirkungen zwischen Nachfrage- und Angebotsseite - wird ein iterativer Kopplungsmechanismus entwickelt, der das Zusammenspiel der Akteure, die in den verschiedenen Modulen abgebildet werden, auf integrierte Weise widerspiegelt. Die einzelnen TAM-Module werden durch einen Austausch von endogen abgeleiteten Energiebedarfen (Strom, Wärme und Wasserstoff) aus den Nachfragesektoren und zugehörigen Preisen aus dem Versorgungssektor gekoppelt, um ein Gleichgewicht zu erreichen. Dieser bilaterale Datenaustausch zwischen den Modellen wird so lange iteriert, bis die Veränderungen der Nachfragen und der Preise in zwei aufeinanderfolgenden Iterationen unter einem bestimmten Schwellenwert – hier 5 % Abweichung – liegen, was als Konvergenz der gekoppelten Modelle interpretiert wird. Die Existenz eines Gleichgewichtspunkts zwischen den verbesserten Sektormodellen garantiert jedoch nicht unbedingt immer auch eine Konvergenz. Um eine Konvergenz zu gewährleisten, wurde der Iterationsansatz leicht überarbeitet, indem Relaxationsfaktoren in den verwendeten Gauß-Seidel-Mechanismus eingeführt wurden. Mit diesem Verfahren wurde für alle simulierten Szenarien nach maximal 14 effektiven Iterationen ein Gleichgewicht erreicht.

In Bezug auf die Iterationen erweist sich das „Carbon-free targets” (CFT) Szenario mit dem Ziel einer klimaneutralen Entwicklung ab dem Jahr 2050 als das herausforderndste Szenario, insbesondere im Hinblick auf die Nachfrage und den Preis der zwischen den Modulen ausgetauschten Energieträger um das Jahr 2050. Hier ist über die Iterationen hinweg zu beobachten, dass die Preis- und Nachfrageabweichungen der ausgetauschten Energieträger zwischen den Iterationen von einem Sektor zum anderen Sektor stark schwanken, was verdeutlicht, wie stark das Gesamtgleichgewicht im Energiesystem durch die multilaterale Interaktion zwischen verschiedenen Sektoren beeinflusst wird. Dadurch wird die Notwendigkeit sektorübergreifender Lösungen betont, wenn ehrgeizige Klimaziele angestrebt werden. Diese Notwendigkeit wäre in einem integrierten Modell nicht so transparent zu erkennen.

Ein weiterer Effekt, der Aufschluss reich und über die Iterationen hinweg zu beobachten ist, ist die wechselseitige Beeinflussung der Preis- und Nachfrageabweichungen für die zwischen den Modulen ausgetauschten Energieträger. Dies gilt insbesondere in den Szenarien mit den ehrgeizigeren Klimaschutzzielen, dem „Carbon tax" (CTX) und dem „Carbon-free targets" (CFT) Szenario. Zu beobachten ist dies hauptsächlich zwischen Strom und Wasserstoff für die Interaktion zwischen dem Verkehrs- und den Bereitstellungssektoren und, in etwas geringerem Maße, zwischen Strom und Wärme für die Interaktion zwischen Haushalts- und Industriesektor. Grund dafür ist die Möglichkeit, Wasserstoff und Wärme aus mit Strom betriebenen Technologien erzeugen zu können, z. B. Elektrolyseure oder Wärmepumpen. Daher zeigt das Iterationsverfahren - transparenter als ein integriertes Modell -, wie sich diese gekoppelten Effekte auf das Gleichgewicht zwischen den Sektoren des Energiesystems gegenseitig beeinflussen.

Der entwickelte Modellkopplungsansatz erweist sich als herausfordernd, aber auch als hilfreich für das Verständnis einzelner Effekte und der Interaktionen zwischen den Modulen. Die Vorteile eines solchen Ansatzes gegenüber einem integrierten Modell sind: 1. die Sektormodelle (Module) konnten getrennt voneinander mit geringeren Komplikationen erweitert werden, was die Einbeziehung sektorspezifischer Überlegungen und Spezifika erleichterte; 2. die Rechenzeit wurde reduziert, da die Sektormodelle parallel betrieben werden konnten; 3. für bestimmte Akteursgruppen konnten Budgetbeschränkungen einbezogen werden, die auch die Entwicklung der Energieträgerpreise mit berücksichtigen. Allerdings war es in Bezug auf die Konvergenz eine Herausforderung, da die Nachfragemodelle sehr empfindlich auf kleine Änderungen der Preise für die ausgetauschten Energieträger reagieren. Dies zeigt andererseits jedoch auch deutlich auf, wo innerhalb des Energiesystems eine hohe Sensitivität vorliegt. Auch diese Effekte könnten in einem integrierten Modell so nicht herausgearbeitet werden.

Politikszenarien

Ein Referenzszenario und zwei alternative Politikszenarien werden entwickelt und getestet, um mit dem neu entwickelten TIMES-Akteursmodell die Auswirkungen auf die Dezentralisierung des deutschen Energiesystems und die Ausgestaltung der dafür notwendigen Rahmenbedingungen zu ermitteln. Dies sind das „Reference" (REF), das „Carbon tax" (CTX) und das „Carbon-free targets" (CFT) Szenario. Eine Szenariovariante "Reserve capacity" (RCA) ermittelt die Bedeutung der Ausgestaltung der Regelungen für die Bereitstellung der Reservekapazitäten im Strommarkt. Für die Szenarioanalyse wird ein umfassender Satz von Rahmendaten angenommen, die die künftige Energienachfrage und die Technologieauswahl beeinflussen. Diese Annahmen basieren auf einer Vielzahl von Quellen, wobei besonderes Augenmerk auf die Konsistenz der Daten gelegt wird. Alle Szenarien beinhalten die methodischen Erweiterungen des TAM-Modells und werden mit dem „Reference“ (REF) Szenario und / oder mit dem aggregierten Modell verglichen, das diese methodischen Verbesserungen nicht beinhaltet.

Ergebnisse

Zunächst zeigt ein Vergleich der Szenarienergebnisse zwischen dem neu entwickelten (disaggregierten) TAM-Modell mit dem aggregierten Modell, das der Ausgangspunkt für die Neuentwicklung war, den Erkenntnisgewinn durch die neu entwickelte Methode. Dann folgt ein Überblick über die Szenarioergebnisse innerhalb des TAM-Modells. Eine Diskussion der Ergebnisse zu der Entwicklung des Gesamtenergiesystems, den Emissionsänderungen, beim Grad der Dezentralisierung und zur Rolle spezifischer Sektoren und Akteure schließt sich an.

Vergleich des TAM-Modells mit den aggregierten Modellergebnissen für das CTX-Szenario

Wichtigste Aussagen:

- Das aggregierte Modell überschätzt die möglichen Veränderungen in den Energieträgerstrukturen und auch die Größenordnungen der produzierten und genutzten Energieträger.
- Zudem unterschätzt das aggregierte Modell die langfristigen Emissionen und überschätzt die Investitionen aufgrund der mangelnden Berücksichtigung des verfügbaren Budgets. Die Budgetbeschränkung begrenzt die Fähigkeit bestimmter Akteure, in CO_2-freie Technologien zu investieren (hohe Vorlaufkosten), so dass sie lieber fortlaufend eine CO_2-Steuer (höhere langfristige Betriebskosten) bezahlen.

Die Auswirkungen der methodischen Verbesserungen, die im TAM-Modell vorgenommen wurden, können im Vergleich mit dem aggregierten Modell ermittelt werden. Dazu werden die Ergebnisse anhand eines Szenarios zur Veranschaulichung bewertet, dem „Carbon tax” (CTX) Szenario. Dieses simuliert eine CO_2-Steuer, die bis 2050 auf 240 € pro Tonne CO_2 steigt.

Der erweiterte Blick auf die verschiedenen Akteure in den Nachfragesektoren zeigt einen differenzierteren Endenergiebedarf, bei dem das aggregierte Modell Art und Umfang der genutzten Energieträger überschätzt. Dies ist weitgehend auf die gemittelten Bedarfe und die fehlende Berücksichtigung von Entscheidungsverhalten und Präferenzen der verschiedenen Akteursgruppen zurückzuführen. Beispielsweise erfüllt im Verkehrssektor das aggregierte Modell die exogen vorgegebene Personenverkehrsnachfrage für jeden Verkehrsträger separat und vernachlässigt dabei den Unterschied in der Entscheidungsfindung der verschiedenen Verbraucher, während das disaggregierte TAM-Modell den Wettbewerb zwischen den Verkehrsträgern zulässt. Diese Option in Verbindung mit der erweiterten Modellierung von Einkommensgruppen zeigt, wie verschiedene Einkommensgruppen unterschiedlich über ihr bevorzugtes Verkehrsmittel entscheiden und wie ihre Entscheidung durch energie- und klimapolitische Maßnahmen beeinflusst werden kann. In ähnlicher Weise ist im Haushaltssektor der Endenergieverbrauch im aggregierten Modell aufgrund der Überschätzung der Auswirkungen der CO_2-Steuer höher, wobei das disaggregierte TAM-Modell dies über fehlende Entscheidungsbefugnisse (für Investitionen) bei Mietern und Haushalten mit niedrigerem Einkommen erklärt.

Die Berücksichtigung der Verfügbarkeit von Finanzierungsmitteln ist für die erfolgreiche Umsetzung der Energiewende von entscheidender Bedeutung. Das disaggregierte TAM-Modell berücksichtigt das gesamte verfügbare Budget für bestimmte Akteursgruppen innerhalb jedes Sektors, das sich auf die Art der getätigten Investitionen auswirkt. Das Fehlen von Budgetbeschränkungen im aggregierten Modell führt dazu, dass die Gesamtemissionen aufgrund der mangelnden Berücksichtigung des verfügbaren Budgets unterschätzt werden. Die Budgetbeschränkung begrenzt die Fähigkeit bestimmter Akteure, in CO_2-freie Technologien zu investieren (hohe Vorlaufkosten), so dass sie lieber fortlaufend eine CO_2-Steuer (höhere langfristige Betriebskosten) bezahlen. Dies betrifft insbesondere im Haushaltssektor die Investitionen in Heizung, Warmwasserbereitung, Sanierung und Mobilität. Im Energiebereitstellungssektor überschätzt das aggregierte Modell das Einsatzpotenzial der Onshore-Windenergie, während das disaggregierte Modell zeigt, wie die Finanzausstattung normalerweise nicht berücksichtigter Akteure, wie z. B. Energiegenossenschaften, dazu beitragen kann, das lokale Potenzial einiger erneuerbarer Ressourcen, insbesondere von Freiflächen-PV, zu erschließen.

Szenarioergebnisse innerhalb von TAM

Wichtigste Aussagen:

- Im Vergleich der Szenarioanalysen, die mit dem neu entwickelten TAM-Modell durchgeführt wurden, wird deutlich, dass sich im Verkehrs- oder Haushaltssektor die Auswirkungen der CO_2-Steuer im „Carbon tax“ (CTX) Szenario nicht von dem Pfad im „Reference“ (REF) Szenario unterscheiden. In diesen Sektoren ist nur ein unmerklicher Einfluss auf das individualisierte Verhalten zu beobachten.

- In allen Szenarien wird die Eigenerzeugungskapazität durch Photovoltaik im Haushaltssektor in einem ähnlichen Muster maximiert, was auf die Budgetbeschränkungen der Haushalte zurückzuführen ist. So investieren die Hauseigentümer zuerst, gefolgt vom Mietwohnungsbau (dessen Erschließung zweifellos nur durch politische Interventionen erreicht werden kann).
- Ohne politische oder finanzielle Interventionen werden im „Reference“ (REF) Szenario fossile Brennstoffe bis weit in die Zukunft dominierend bleiben. Unter diesen Bedingungen wird das Potenzial der Akteure in allen Sektoren nicht voll ausgeschöpft werden, um die Ziele der Energiewende zu erreichen. Aufgrund der geringen Anreize für die Elektrifizierung und die Nutzung alternativer Energieträger, z. B. Wasserstoff, wird im „Reference“ (REF) Szenario das Potenzial der Prosumenten und für eine Dezentralisierung nicht voll ausgeschöpft.
- Obwohl die Einführung einer CO_2-Steuer im „Carbon tax“ (CTX) Szenario auch ohne weitere Regulierungen das Energiesystem in Richtung einer stärkeren Dekarbonisierung verschiebt, reicht dies für eine vollständige Dekarbonisierung in allen Sektoren, wie z. B. im Verkehrssektor, noch nicht aus. Aufgrund eines teilweisen Ersatzes von fossilen Brennstoffen durch Strom zur Emissionsminderung auf der Nachfrageseite scheint sich das Potenzial der Prosumenten für die Eigenerzeugung gegenüber dem „Reference“ (REF) Szenario zu verringern.
- Die vollständige Dekarbonisierung bis 2050, wie sie im „Carbon-free targets“ (CFT) Szenario untersucht wurde, ist nur durch den verstärkten Einsatz von Eigenerzeugung und dezentralen Quellen erreichbar. Dies erfordert jedoch auch eine verstärkte Dekarbonisierung der Energiebereitstellung durch den Versorgungssektor, der die Änderungen auf der Nachfrageseite durch eine verstärkte Bereitstellung von CO_2-freiem Strom und von über Elektrolyse erzeugtem Wasserstoff ergänzt. Insgesamt zeigt sich, dass die Erhöhung des Anteils der dezentralen Eigenerzeugung in Verbindung mit einer Stärkung der zentralen Energieversorgung, z. B. von Strom, Wasserstoff und Fernwärme, wesentliche Elemente eines kostengünstigen und klimafreundlichen Energiesystems darstellen, das gleichzeitig die Bedürfnisse und das Verhalten der Akteure adäquat berücksichtigt.

Um die Auswirkungen auf die Dezentralisierung des deutschen Energiesystems und die Ausgestaltung der dafür notwendigen Rahmenbedingungen zu ermitteln, werden mit TAM drei Hauptszenarien analysiert: „Reference” (REF), „Carbon tax” (CTX) und „Carbon-free targets” (CFT) Szenario.

Das „Reference” (REF) Szenario beschreibt die Entwicklung des deutschen Energiesystems unter Berücksichtigung bestehender politischer Maßnahmen. Unter Berücksichtigung von Budgetbeschränkungen sowie des Akteursverhaltens werden das Fernwärme- und das Biomassepotenzial weitgehend ausgeschöpft, insbesondere bei den Haushalten und in der Industrie. Zusätzlich zum Ausbau dieser CO_2-armen Energieträger gibt es kaum Anreize für eine weitergehende Dekarbonisierung. So baut die Industrie sowohl für die industrielle Produktion als auch längerfristig bei der Eigenerzeugung in großem Maße auf nicht erneuerbare Energiequellen. Die Haushalte nutzen nach wie vor Gas, um den Bedarf an Warmwasser und Raumwärme zu decken. Im Individualverkehr werden weiterhin Autos mit Verbrennungsmotoren eingesetzt, um die Verkehrsnachfrage zu befriedigen. Für Stadtwerke und Energiegenossenschaften ist der Anreiz geringer, sich an der Bereitstellung von Energie aus den wichtigsten erneuerbaren Energiequellen, Wind und Photovoltaik, zu beteiligen, so dass institutionelle Investoren und Versorgungsunternehmen die Strombereitstellung aus diesen beiden Quellen sowie insbesondere bei der Offshore-Windenergie dominieren. Die Strom- und Fernwärmeerzeugung aus fossilen Brennstoffen, insbesondere Erdgas, wird im „Reference" (REF) Szenario bis zum Ende des Modellierungszeitraumes weiter bestehen, allerdings mit allmählich abnehmendem Anteil. Ohne weitere politische oder finanzielle Interventionen werden fossile Brennstoffe bis weit in die Zukunft hinein dominierend bleiben. Unter diesen Bedingungen wird das Potenzial der Akteure in allen Sektoren nicht voll ausgeschöpft werden, um die Ziele der Energiewende zu erreichen. Aufgrund der geringen Anreize für die Elektrifizierung und die Nutzung alternativer Energieträger, z. B. Wasserstoff, wird im „Reference" (REF) Szenario auch das Potenzial der Prosumenten und für eine Dezentralisierung nicht voll ausgeschöpft.

Die Einführung von CO_2-Steuern im Rahmen des „Carbon tax" (CTX) Szenarios ist ein starker Impuls zur Reduzierung des Einsatzes fossiler Brennstoffe. In den Sektoren wirkt sie jedoch auf verschiedenen Ebenen, so dass sie nicht als alleinige Lösung für ein vollständig dekarbonisiertes System dienen kann. Die akteursbasierte Modellierung dieses Szenarios impliziert einen spürbaren Anstieg der Stromnachfrage. Die Industrie zeigt erhebliche Emissionsreduktionen, wenn man sie als Ganzes betrachtet. Ein tieferer Blick in die einzelnen Branchen macht aber deutlich, dass die Höhe der eingeführten CO_2-Steuer nur kleinere Verschiebungen bewirkt. Dies deutet darauf hin, dass eine CO_2-Steuer für eine tiefergehende Dekarbonisierung aller Industriesektoren alleine nicht ausreichend ist. Der Erdgasverbrauch für Heizzwecke im Haushaltssektor wird im „Carbon tax" (CTX) Szenario nur teilweise durch elektrische Wärmepumpen ersetzt, hauptsächlich in Einfamilienhäusern in städtischen Gebieten. Im Gegensatz dazu wird der Personenverkehrssektor nach wie vor auf mit fossilen Brennstoffen betriebene Pkw angewiesen sein, ein Ergebnis, das mit dem „Reference" (REF) Szenario nahezu identisch ist. Dies unterstreicht die besondere Situation bei der Entscheidungsfindung der Verbraucher in diesem Sektor. Bei der Energiebereitstellung führen die angenommenen CO_2-Steuern des „Carbon tax“ (CTX) Szenarios zu einer fast vollständigen Dekarbonisierung des Sektors bis 2060. Um dies zu erreichen, sollten Energiegenossenschaften stärker als im „Reference” (REF) Szenario in Onshore-Windenergie und Freiflächen-PV investieren. Insgesamt zeigt das „Carbon tax“ (CTX) Szenario, dass die Einführung hoher CO_2-Steuern ohne weitere Regulierungen das Energiesystem stärker dekarbonisiert. Für eine vollständige Dekarbonisierung in allen Sektoren, z. B. im Verkehrssektor, reicht dies jedoch noch nicht aus. Zur Emissionsminderung erfolgt auf der Nachfrageseite teilweise eine Substitution von fossilen Brennstoffen durch Strom. Mit der höheren Stromnachfrage mindert sich die Bedeutung der Eigenerzeugung der Prosumenten in der gesamten Strombereitstellung im Vergleich zum „Reference” (REF) Szenario.

Das „Carbon-free targets” (CFT) Szenario untersucht unter Berücksichtigung des Akteursverhaltens den kostenoptimalen Weg zur Dekarbonisierung des deutschen Energiesystems bis 2050. Die Dekarbonisierung erfordert eine erhebliche Substitution zwischen den genutzten Energieträgern und bedeutet eine Umstrukturierung auf der Angebotsseite sowie Investitionen in CO_2-freie alternative Technologien in den Nachfragesektoren. Um dieses Ziel zu erreichen, ist eine Verlagerung des Energieverbrauchs in den Nachfragesektoren von fossilen Brennstoffen wie Gas und Mineralölprodukten hin zu Sekundärenergieträgern wie Strom, Fernwärme und Wasserstoff zu beobachten, die stärker zentralisiert bereitgestellt werden. Dieser Trend geht einher mit Investitionen in dezentrale Energiequellen, wie z. B. dem Biomasseeinsatz in der industriellen Eigenerzeugung oder in den Haushalten zum Heizen, sowie mit einer Zunahme des Einsatzes von Wärmepumpen auf der Basis von Umgebungs- und Erdwärme im Haushaltssektor – was den Bedarf an zentralisiert bereitgestelltem Strom erhöht. Die verstärkte Nutzung von Wasserstoff durch die Nachfragesektoren verstärkt zudem den Strombedarf, der über den Versorgungssektor bereitgestellt werden muss und in die Elektrolyse eingespeist wird. Eine Dekarbonisierung im Verkehrssektor ist nur mit einer Verlagerung hin zu Elektro- und Wasserstofffahrzeugen sowie einer verstärkten Nutzung des öffentlichen Verkehrs möglich. Das Ziel der Klimaneutralität verändert auch die Energiebereitstellungsseite, wo sich Chancen für eine vielfältigere Palette von Akteuren eröffnen. Alle Akteure investieren in erneuerbare Energien, jedoch in ein unterschiedliches Portfolio. Institutionelle Anbieter dominieren die Nutzung der Onshore-Windenergie, die großen Energieversorger nehmen in Hinblick auf die Offshore-Windenergie eine bedeutendere Rolle ein. Energiegenossenschaften zielen auf Investitionen in Freiflächen-PV ab, treten aber auch stärker in den Onshore-Windmarkt ein. Insgesamt zeigt sich, dass die Erhöhung des Anteils der dezentralen Eigenerzeugung in Verbindung mit einer Stärkung der zentralen Energieversorgung, z. B. von Strom, Wasserstoff und Fernwärme, wesentliche Elemente eines kostengünstigen und klimafreundlichen Energiesystems darstellen, das gleichzeitig die Bedürfnisse und das Verhalten der Akteure adäquat berücksichtigt. Das CO_2-arme Energiesystem der Zukunft wird eine Mischung aus zentralen und dezentralen Elementen aufweisen.

Diskussion und Schlussfolgerungen

Die durch die Anwendung des TIMES-Akteursmodells (TAM) gewonnenen Erkenntnisse zeigen, dass die durchgeführten methodischen Erweiterungen bezüglich der verbesserten Darstellung der Akteure zu einer besseren Einschätzung der angebots- und nachfrageseitigen notwendigen Veränderungen führen. Das entwickelte und angewandte Verfahren der Modellkopplung bietet eine ganzheitliche Sicht auf ein integriertes Energiesystem in seiner Gesamtheit mit einer verbesserten Darstellung der Akteure, womit anwendbare innovative Lösungen zur Reduktion der Treibhausgas-(THG-)Emissionen erarbeitet werden können, die für die verschiedenen Akteure innerhalb der verschiedenen Sektoren relevant sind. Die Methodik eignet sich auch dazu, die Herausforderungen bei der politischen Koordination zwischen ähnlichen Akteuren zu bewältigen und die Konsistenz bei der Modellanwendung zur Definition CO_2-armer Transformationspfade zu erhöhen. Diese Erkenntnisse können für die Entwicklung von Politikinstrumenten zur Technologieförderung und zum Marktdesign genutzt werden. Damit können die Akteure unter Berücksichtigung ihrer nicht-technischen Entscheidungskriterien gezielter bezüglich der Investitionsentscheidungen angesprochen werden, was die Kostenwirksamkeit bei der Erreichung der Ziele der Energiewende deutlich steigern kann.

Die Ergebnisse des neu entwickelten TIMES-Akteursmodells (TAM) im Vergleich mit dem aggregierten Modell, das den Ausgangspunkt für die Modellerweiterungen dargestellt hat, zeigt, dass die typischer Weise in der Energieplanung verwendete aggregierte Methode sowohl den Energieverbrauch überschätzt als auch die gesamten Emissionen unterschätzt. Die notwendigen Veränderungen in der Industrie sollten darauf abzielen, den Anteil erneuerbarer Energiequellen am Energiemix zu erhöhen, indem vor allem eine zuverlässige Versorgung mit Biomasse gewährleistet wird, und Technologien zur CO_2-Abscheidung für industrielle Prozesse einzusetzen, die aufgrund prozessbedingter Emissionen ansonsten nicht weiter dekarbonisiert werden können. Im Haushaltssektor sind kurz- bis mittelfristig Investitionen erforderlich, die darauf ausgerichtet sein sollten, die Eigenversorgung zu stärken und zudem das Potenzial im Mietwohnungsbau zu nutzen, insbesondere in städtischen Mehrfamilienhäusern. Finanzielle und gesetzgeberische Unterstützung für die Reduktion der Nachfrage durch Gebäudesanierung und die Marktdurchdringung von Wärmepumpen und Solarthermieanlagen ergänzen dies. Der

Personenverkehrssektor bringt die höchsten marginalen Kosten bei der Emissionsminderung mit sich, nicht nur wegen der kostspieligen Infrastruktur und der Flottenerneuerung. Hier geht auch das Entscheidungsverhalten der Verbraucher ein, das immaterielle Kosten, wie z. B. die Reisezeit, einschließt, was sich negativ auf die Nutzung zum Teil effizienterer öffentlicher Verkehrsmittel (ÖPNV) auswirkt. Daher sind einfache Preisaufschläge für den Verbrauch fossiler Brennstoffe unzureichend, um ihn in Richtung Dekarbonisierung zu lenken. Innerhalb des Energiebereitstellungssektors könnte jede Akteursgruppe mit den jeweiligen spezifischen Finanzierungsbedingungen in jeder modellierten Region innerhalb Deutschlands in ein bestimmtes Technologieportfolio investieren, so dass das gesamte Energiesystem die Ziele der Energiewende zu möglichst geringen Systemkosten erreicht. Beispielsweise sollten Finanzinstitutionen ihr Hauptaugenmerk auf die Onshore-Windenergie legen, insbesondere im Norden, die Versorgungsunternehmen sollten sich auf das Potenzial der Offshore-Windenergie konzentrieren und zudem die Verfügbarkeit ausreichender Netz- und Reservekapazitäten sicherstellen und die Energiegenossenschaften könnten ihr verfügbares Kapital für Investitionen in die Freiflächen-PV, insbesondere im Süden Deutschlands, zur Verfügung stellen.

Insgesamt sind alle Sektoren in der Lage, ihre Treibhausgas-(THG-)Emissionen deutlich zu reduzieren, wobei sich jedoch einige Sektoren damit deutlich leichter tun als andere. Im „Reference" (REF) Szenario werden die THG-Emissionen im Jahr 2050 insgesamt um 66,3 % im Vergleich zu 2015 reduziert. In der Energiebereitstellung ist es im Vergleich zwischen 2050 und 2015 eine Minderung um 96,3 %, bei den industriellen Prozessemissionen um 44,7 %, bei den energiebedingten THG-Emissionen der Industrie um 74,6 %, bei den Haushalten um 58,1 %, beim Individualverkehr um 19,1 %, beim ÖPNV um 77,1 % und bei den restlichen THG-Emissionen um 34,8 %. Im Vergleich zum „Reference" (REF) Szenario verringern sich im gleichen Zeitraum im „Carbon tax" (CTX) Szenario die THG-Emissionen insgesamt um zusätzliche 11,0 %. Das „Carbon-free targets" (CFT) Szenario verringert die THG-Emissionen um zusätzliche 28,4 %, was verdeutlicht, dass die im „Carbon tax" (CTX) Szenario angenommenen Höhen der CO_2-Steuer alleine nicht ausreichen, um Klimaneutralität zu erreichen. Tiefergehende Emissionsminderungen sind in den schwerer zu dekarbonisierenden Sektoren wie Industrie und Verkehr nur möglich, wenn die Energienachfrage in der Industrie über Energieeffizienzverbesserungen insgesamt gesenkt wird und gleichzeitig in Carbon Capture and Storage-(CCS-)Technologien in der Industrie investiert wird. Im Verkehr sollte auf andere Verkehrsträger umgestellt werden, d. h. der Modal-Split angepasst werden, und es sollten verstärkt CO_2-freie Energieträger, wie z. B. Wasserstoff, eingesetzt werden. Es ist in allen Sektoren von wesentlicher Bedeutung, die hohen Vorab-Investitionskosten überwinden zu können, was zusätzlich zur CO_2-Steuer durch eine andere Art von Politikinstrumenten umgesetzt werden sollte.

Insgesamt besteht das Ziel der Szenarioanalyse mit dem TIMES-Akteursmodell (TAM) darin, Orientierung für die Frage zu geben, wie eine optimale Mischung aus dezentralen und zentralen Technologien aussehen kann. Dies wird anhand des Grades der Dezentralisierung im Energiesystem über den Anteil der Stromeigenerzeugung in den Nachfragesektoren an der gesamten Stromerzeugung gemessen. Bezüglich der Eigenstromerzeugung hat über alle Sektoren und alle Szenarien hinweg die Photovoltaik mit Dachanlagen die größte Bedeutung, wobei die höchsten Beiträge von den Haushalten und den anderen Sektoren („Rest“ – Landwirtschaft, Handel, Güterverkehr) kommen. Werden keine zusätzlichen Emissionsminderungsanstrengungen unterstellt („Reference” (REF) Szenario), dann stellen die Kohlen einen wichtigen Brennstoff für die Eigenerzeugung im Industriesektor dar. Im „Carbon-free targets” (CFT) Szenario verlagert sich der Schwerpunkt auf die Nutzung erneuerbarer Industrieabfälle. Auch die Bioenergie und die Windenergie haben im „Carbon-free targets” (CFT) Szenario eine größere Bedeutung, da hier CO_2-freie Erzeugungsoptionen erforderlich sind, um die Ziele zu erreichen.

Ein Vergleich des Grades der Dezentralisierung im Jahr 2050 macht deutlich, dass Klimaneutralität nicht notwendigerweise durch ein vollständig dezentralisiertes oder ein stärker dezentralisiertes Energie- bzw. Stromsystem erreicht wird. Der geringste Grad der Dezentralisierung, wie er im vorliegenden Vorhaben definiert ist, wird mit 24,2 % im „Carbon-free targets” (CFT) Szenario und der höchste Grad im „Reference” (REF) Szenario mit 35,3 % erreicht. Dies deutet darauf hin, dass der Energiebereitstellungssektor eine bedeutende Rolle bei der Sicherstellung der Erreichung der Emissionsminderungsziele einnehmen sollte. Im „Reference” (REF) Szenario beträgt die Nettostromerzeugung im Jahr 2050 jedoch nur 504,5 TWh im Vergleich zu den 760,8 TWh des „Carbon-free targets” (CFT) Szenarios. Im „Carbon-free targets” (CFT) Szenario stützt sich die Eigenerzeugung im Industriesektor immer noch auf fossile Brennstoffe, wobei die höheren CO_2-Pönalen die Kosteneffizienz dieser Erzeugung begrenzen. Die Haushalte zeigen mit größeren Dezentralisierungsanteilen im „Reference” (REF) Szenario dasselbe Muster, was darauf hindeutet, dass Haushalte für die Emissionsminderungen im „Carbon-free targets” (CFT) Szenarios auf CO_2-freie, zentral bereitgestellte Sekundärenergieträger wie Strom und Fernwärme angewiesen sind, um die Ziele zu erreichen. Darüber hinaus sollten ÖPNV-Anbieter die Möglichkeit nutzen, Strom für den Eigenverbrauch zu erzeugen, indem sie mittelfristig (2025 bis 2045) in Onshore-Windtechnologien investieren. Mit dem angenommenen weiteren Rückgang der PV-Erzeugungskosten unter die langfristigen Erzeugungskosten der

Onshore-Windenergie sollten sie jedoch nach 2040 vermehrt in Freiflächen-PV investieren. Für die Strombereitstellung muss demnach eine Ausweitung der dezentralen Eigenerzeugung Hand in Hand gehen mit einer Stärkung der zentralen Energieversorgung.

TAM bildet als Akteursmodell das jeweilige Entscheidungsverhalten hinsichtlich der Investition in dezentrale Technologien und deren Einsatz bzw. die Reaktion auf Veränderungen der residualen Last unter den jeweiligen Rahmenbedingungen ab. Die Modellierung des deutschen Energiesystems dient dazu, das Anwendungspotenzial des neu entwickelten TAM-Modellansatzes und die möglichen Veränderungen von Rahmenbedingungen aufzuzeigen. Mit Hilfe des neu entwickelten Modellierungstools können Fragen nach der Bedeutung des Potenzials einer Dezentralisierung der Energiesystems und der Einbindung der Akteure bearbeitet werden. Darüber hinaus können Gebäudesanierungs- oder eine energiewirtschaftliche Verkehrsstrategie als Teile der Energiewende eingehend untersucht werden. Daraus lassen sich die Gestaltungsoptionen eines intelligenten, kombiniert zentral-dezentral ausgerichteten Energiesystems und seine technologischen Optionen mit ihren ökonomischen, ökologischen und systemischen Potenzialen sowie sozialen Aspekten evaluieren.

Die Methodik wurde anhand des deutschen Energiesystems entwickelt und angewendet. Sie kann dazu beitragen, Erkenntnisse für konkrete akteursspezifische Politikempfehlungen zu gewinnen und eine anwendbare Roadmap für die Dekarbonisierung des Energiesystems zu identifizieren, die gute Chancen hat, effektiv und akteursübergreifend umgesetzt zu werden.

Transferpotenzial

Das TIMES-Akteursmodell (TAM) erleichtert dank des entwickelten und umgesetzten Kopplungsansatzes zwischen den verschiedenen Modulen die Berücksichtigung der Charakteristika, Potenziale und Grenzen verschiedener Akteure in jedem Sektor (Haushalte, Großverbraucher, Energieversorger). Dennoch liefert es auch den Rahmen für integrierte Untersuchungen des Energiesystems. Daher kann TAM einerseits als Instrument für die Politikberatung eingesetzt werden, um Transformationspfade für das gesamte Energiesystem abzubilden, wobei auch die Auswirkungen von Politikinstrumenten auf der Ebene der Akteure aufgezeigt werden können. Andererseits kann TAM aber auch genutzt werden, um zu analysieren, wie auf bestimmte Akteure innerhalb eines bestimmten Energiesektors ausgerichtete Politikinstrumente andere Sektoren und das gesamte Energiesystem beeinflussen können. Da die Sektormodelle in TAM auch losgelöst voneinander einsetzbar sind, können sie auch für Studien verwendet werden, die sich auf einen oder mehrere spezifische Sektoren beschränken.

The main points at a glance

The Paris Agreement reinforces the need for an imminent transition towards a low carbon economy that includes alternative clean technologies to be promoted to reduce the emissions. As a result, the German energy system is increasingly becoming diverse and decentralised through the variable spatial distribution of the renewable energy resources, heterogeneity of actors and the variety of technologies and policies. These diversities offer flexibility and facilitate the active participation of energy producers and consumers while increasing the complexity of ensuring that the ambitious goals of the energy transition are met in a cost effective manner. Yet, the German energy transition targets are quite challenging, particularly for a complex system consisting of diverse actors located in different environments facing several alternative generation and end-use technologies. On the one hand, the transition should not cause adverse financial effects to actors nor hinder their ability to fulfil their energy demands. On the other hand, the actors' diverse characteristics could simultaneously serve the system in its transition in that different actors are more cost-effectively assigned to take different roles based on their potential.

Decentralisation means fulfilling the energy demand through a multitude of smaller units located close to consumption. The anticipated decentralisation of energy generation makes the provision of a reliable supply more complex. Therefore, beside the crucial role of actors in the supply sector, consumers of energy are at the core of the energy transition and have a critical role to increase the efficient use of energy or to be prosumers thereby shaping the future structure of the energy system. Technological changes through investments in low-carbon technologies will be vital to achieve decarbonisation, but the social, economic and behavioural aspects are equally important in determining consumers' operation and investment decisions.

The Energy-Environment-Economy-Engineering (E4) models have long supported the formulation of energy policy by representing environmental, economic and technological dimensions of the integrated energy system. Although these types of models are powerful tools for analysing the least-cost decarbonisation pathways, most models represent energy systems by a few average actors representing large groups of consumers or producers and thus fail to incorporate the unique economic, technical and rational behavioural characteristics of the different players, which can consequently lead to inaccurate results and hence unrealistic policy design. Therefore, these models are not able to take into account the decentralisation of technologies since investments in decentralised technologies are quite often driven by diverse socio-economic and financial characteristics of actors. So, there is a need to enhance actor representation in order to be able to analyse both policy implementation aspects and the design of long-term low-carbon transition more accurately.

To model decentralisation for energy system planning and better support policymaking, the concept of this project is built around the recognition of current gaps in decision support tools and aimed at improving the representation of both supplier and consumer actors in energy system modelling. The objective of this research is to examine the optimum share of centralised and decentralised technologies in the overall German energy system. In order to address this, methodological extensions with the aim of enhancing the representation of multiple heterogeneous actors are performed.

Methodology

The TIMES Actors Model (TAM) developed in this study takes these factors into account with an improved representation of unique financial and socio-economic characteristics of heterogeneous supplier and consumer actor groups across the energy system considering their specific operation and investment decision-making to investigate the optimum structure of centralised and decentralised generation in the German energy system. To analyse the decentralisation tendencies, a methodological approach is developed which allows the different decision situations of the diverse actors in different sectors to be modelled while recording the effects on the development of the whole system. Thus, the overall German energy system is investigated through separate sector models. The sectoral models are then combined via coupling mechanisms to represent the entire energy system. The combination of the coupled sector models is named TAM.

The first step to include decentralisation in TAM is to disaggregate the actors who play a role in the energy transition. Then, the heterogeneous financial and socio-economic characteristics of both supplier and consumer actors is taken into account. The financial aspects of actors in industry, providers of passenger transport, the supply sector and the realistically available budget of households within seven income groups to meet electricity, heat and mobility demands are represented in the model. All sectors are calibrated to the base years 2013 and 2015 and the modelling horizon is until 2060. The sector models are described at an annual level while the spatial resolution of the model is on a national scale covering all of Germany, with the exception of the supply sector consisting of four regions within Germany. Other consumers such as agriculture, commerce and freight transport are represented in a simplified way to have a full picture of the entire energy system. TAM includes environmental pollutants such as CO_2, CH_4 and N_2O as well.

Each sector is characterised based on specific intricacies. For example, the industrial enterprises are characterised by a large number of different actors and thus divergent decision-making situations are disaggregated based on industrial branches into different 'actor groups' according to company size and production route and implementing a higher level of technological representation (through breakdown of production processes). Moreover, the investment portfolio is expanded by implementing options for technology retrofits for existing processes, best available technologies, innovative technologies identified to have high decarbonisation potential (including both industrial specific technologies and carbon capture and storage technologies) and self-generation of electricity, heat and hydrogen.

The household sector expresses the heterogeneity of this sector through socio-economic characteristics, buildings type, urbanisation, access to different end-use technologies and the diversity of decision-making situations in households. This disaggregation better describes the investments in renewable technologies or energy efficient appliances and energy retrofits for households. The investment limitations of specific profiles are represented through household budget constraints based on the available savings and the typical expenditure on energy-use appliances and on energy-related home improvements for each income group.

The methodological improvements in the passenger transport sector, enhance the behavioural realism of operation and investment decision of actor groups. The transport demands are disaggregated by trip length and location assigned to the different income groups (i.e., consumer actors who are households). Beside the fuel commodities, the transport technologies consume "money" and "time" commodities. As a result, the Travel Money Budget (TMB), Total Investment Budget (TIB) and Travel Time Budget (TTB) are introduced as commodities across different income groups. These commodities allow the model to choose the cheaper available mode of transport to fulfil demand more quickly. Therefore, the model allows competition to shift to alternative modes of transport for meeting travel demand, e.g., using public transport instead of a private car for heterogeneous households. The public investment budget (PIB) is also introduced in the model. The public transport service provider actors are allowed to invest in new technologies and expand the infrastructure provided that the investment is less than their available budget. Moreover, public transport service provider actor groups could decide to invest in renewable-based decentralised self-generation based on available budget.

Within the energy supply sector, one of the most important factors affecting this sector's decarbonisation is the uneven regional distribution of renewable potentials as well as the demand and the need for long range renewable electricity transmission. Moreover, there are also different actors in the supply sector which have different investment valuation, return expectations as well as budget restrictions and therefore technology choices, which adds to the heterogeneity of this sector. The methodological improvements executed within the supply sector of TAM include four major steps: 1) the investors in public power and heat generation technologies are disaggregated to three main actor groups 2) the actors' specific budget restrictions as a restricting factor for investment decisions are introduced into the model, 3) regional division of the German supply sector into four regions, 4) integrating grid aspects into the model across regions. In this way the heterogeneous optimal investment behaviour of the actors towards decentralisation in different regions within Germany could be captured and addressed further in designing policy instruments targeting the decarbonisation of the German supply sector. The rest of the supply sector, i.e. fuel mining, processing and transportation are also modelled though in an aggregated manner, such as biomass and biogas generation from energy crops, refineries, coal processing, etc.

Model Coupling

In order to have a full picture of the energy system an iterative coupling mechanism based on the Gauss-Seidel iterative method is developed reflecting the interplay between the actors in an integrated way. The individual TAM sector models are coupled through exchange of endogenously derived commodity demands (electricity, heat and hydrogen) by the demand sectors and prices by the supply sector to reach the equilibrium. The coupling process exchanges data between models in an iterative manner for each scenario and ends when an acceptable level of maximum errors below 5% across two successive iterations are reached. Some convergence barriers could be resolved through model improvements. However, the existence of an equilibrium point between the improved sector models does not necessarily guarantee a convergence. To overcome this, the iteration approach was revised through the addition of relaxation factors to the Gauss-Seidel iterative method.

In terms of the iterations, the carbon-free targets scenario (CFT) with a carbon-free target in 2050 and beyond proves to be the most challenging policy scenario with the demand and price of the exchanging commodities due to the strict requirement in 2050. Here, we observe that the iteration prices and demands error of the exchanged commodities around 2050 fluctuate from one sector to another sector across iterations, highlighting how significantly the overall equilibrium in the energy system is influenced by the multilateral interaction among different sectors. This underpins the need for cross-sectoral solutions when aiming for ambitious climate targets, which would otherwise not be as visible in an integrated model.

Another insightful effect observed across the iterations is the coupled development of the price and demand errors for the exchanging commodities especially in the more restrictive and ambitious energy policy scenarios, namely carbon tax (CTX) and carbon-free targets (CFT). This occurs mostly between electricity and hydrogen for the transport-supply sectors interaction, since hydrogen can be generated by decarbonised technologies that run on electricity, such as electrolysis. Therefore, the iteration procedure shows - more transparently than an integrated model - how these coupled effects impact the equilibrium between energy system sectors.

The developed model coupling approach proved possible but challenging. The advantages of such an approach over an integrated model are: firstly, the sector models could be extended separately with much less complication and conflicts which facilitated inclusion of sector-specific considerations. Secondly, it reduced the computation time, since the sector models could be run in parallel, and thirdly allowed the inclusion of budget constraints for particular actor groups including the costs of consumed energy carriers. However, it was challenging with respect to convergence, given the high sensitivity of the demand model choices to small changes in the exchanged commodity prices. Nevertheless, this challenge emphasises where in the energy system the high sensitivity of the optimisation model lies, which would not be visible in an integrated model.

Policy scenarios

One reference scenario and two alternative policy scenarios are developed and tested to determine the effect on decentralisation of the German energy system and the necessary framework conditions: Reference (REF), carbon tax (CTX) and Carbon-free targets (CFT) scenarios. Additionally, the Reserve capacity (RCA) scenario works as a variant to analyse the role of the market design in the electricity sector. A comprehensive set of input assumptions that influence future energy demand and technology choice is established. All scenarios include the methodological extensions of TAM and are compared to the reference scenario (REF) and/or to the aggregated model before improvements.

Results

First, an overview comparing TAM (disaggregated) model with the aggregated model provides an insight into the value of this method. Secondly, an overview of the scenario results within TAM is given. This is followed by a discussion of the results which includes an insight into the overall energy system development, emissions, degree of decentralisation and role of specific sectors and actors.

Comparison of the TAM model with the aggregated model[1] results for the CTX scenario

Key messages:

- The aggregated model **overestimates types and magnitudes of energy carriers** produced and consumed.
- The aggregated model **underestimates the long-term emissions** and overestimates the investments due to the lack of recognition for available budget limiting the ability of specific actors to invest in carbon-free technologies (high upfront costs) instead paying the carbon tax (higher long-term operation costs)

The effects of the methodological improvements made in the new TAM model, the disaggregated model, can be compared to the aggregated model, based on TIMES-D, through the assessment of the results taking one scenario for illustrative purposes, carbon tax (CTX), which includes a carbon tax allocated to the production of CO_2 increasing to 240€ per ton of CO_2 in 2050.

The expanded view into the different actors in the demand sectors shows differentiated final energy demands where the aggregated model overestimates the types and magnitude of fuels consumed. This is largely due to assumptions based on averaged demands and lack of recognition for decision-making power and preferences of different actor groups. For example, in the transport sector the aggregated model fulfils the exogenously given passenger travel demand for each transport mode neglecting the difference in decision-making of different consumers, while the disaggregated TAM model allows for competition among transport modes. This feature coupled with the possibility of modelling the income groups shows how various income groups decide differently on their preferred means of transport and how their decision may be influenced by environmental policies. Similarly, in the household sector the final energy demand is higher in the aggregated model due to the overestimation of the impact of the carbon tax, where the disaggregated TAM model accounts for the lack of decision-making power (i.e., for investments) in tenants and lower-income households.

The consideration of the availability of funding is crucial to the successful implementation of the energy transition. The disaggregated TAM model accounts for the total available budget for particular actor groups within each sector which impacts the types of investments made. The absence of budget constraints in the aggregated model results in the underestimation of the total emissions due to the lack of recognition for available budget limiting the ability of

[1] Based on TIMES-D (Haasz 2017a)

specific actors to afford the high upfront costs of carbon-free technologies rather than paying the carbon tax, which has lower upfront but higher long-term costs overall. This particularly affects households for heating, water heating, renovation and mobility investments. In the supply sector, the aggregated model overestimates the economic potential of onshore wind, while the disaggregated model shows how the financial capacity of overlooked actors can help to unlock the local potential of some renewable resources, especially ground-mounted PV.

Scenario results within TAM

Key messages:

- The impact of the carbon tax in the carbon tax scenario (CTX) is virtually indistinguishable from the pathway in the reference scenario (REF), where **imperceptible influence in individualised behaviour** in the transport or household sectors can be observed.
- Across all scenarios, the **self-generation capacity through PV** in the household sector is maximised in a similar pattern attributed to the budget constraints so that home owners invest first, followed by the rental sector (which undoubtedly only can be achieved through political intervention to tap into the rental sector).
- Without policy or financial interventions in the reference scenario (REF), fossil fuels will remain a dominant fuel source well into the future and actors' potential in all sectors cannot be fully utilised to achieve the environmental targets. Due to little incentive for electrification and use of alternative fuels, e.g. hydrogen, **the potential of prosumers and the degree of decentralisation is overestimated** in the reference scenario (REF) as well.
- Although the imposition of high carbon taxes in the carbon tax scenario (CTX) without any other regulations shifts the energy system towards a greater decarbonisation, it is still not enough for a full decarbonisation in all sectors such as the transport sector. Due to a partial shift from fossil fuels to electricity on the demand side to mitigate emissions, the **potential of the prosumers for self-generation** seems to fade from what was seen in the reference scenario.
- **Decarbonisation by 2050** as investigated in the carbon-free targets scenario (CFT) is achievable only through the increased use of self-generation and decentralised sources together with carbon capture technologies in for industrial processes. However, this requires the increased decarbonisation of generation by the supply sector, which supplements consumption with an increased supply of carbon-free electricity and the use of hydrogen produced via electrolysis.

Three main scenarios are compared within the TAM model: the reference (REF), carbon tax (CTX) and carbon-free targets (CFT) scenarios. This section explores the outcomes resulting from each scenario.

The **reference scenario (REF)** describes the current pathway of the energy system considering existing policy measures. The cost-optimal future along this corridor includes maximising the district heating and biomass potential, especially in households and industry, taking into account budget constraints as well as different actors' behaviour. Despite the inclusion of these carbon-free energy carriers, there is little financial incentive to decarbonise. For instance, industry utilises large amounts of non-renewable sources for both industrial production technologies and self-generation technologies far into the future. Households remain reliant on gas to fulfil water heating and heating needs and private transport continues to use internal combustion engine cars to fulfil the travel demand. There is less impetus for smaller energy suppliers to engage in the provision of energy from main renewables, wind and photovoltaic as citizens energy cooperatives, and so institutional investors and utilities will dominate the supply of energy from these two sources, especially offshore wind. Electricity and heat generation from fossil fuels, particularly natural gas, will continue to exist in this scenario until the end of the modelling time horizon though with gradually decreasing share. Without policy or financial interventions, fossil fuels will remain a dominant fuel source well into the future and actors' potential in all sectors cannot be fully utilised to achieve the environmental targets with little incentive for electrification and use of alternative fuels, e.g., hydrogen, the potential of prosumers and the degree of decentralisation is overestimated in the reference scenario (REF) as well.

The introduction of carbon taxes in the **carbon tax scenario (CTX)** is a strong impulse for reducing consumption of fossil fuels. However, it affects sectors on different levels and cannot serve as the ultimate solution for a fully decarbonized system. The actor's based modelling for this scenario implies a noticeable increase in electricity demand due to higher degree of overall electrification. The industry shows significant emission reductions when considered as a whole. However, a deeper look at the individual industries makes it clear that the amount of the CO_2 tax introduced only causes minor shifts. This indicates that a CO_2 tax alone is not sufficient for a deeper decarbonisation of all industrial sectors. Natural gas consumption for heating in the household sector will be only partly replaced by electric heat pumps mainly by single family households in urban areas. In contrast, the passenger transport sector will still rely on fossil fuelled private cars almost identical to the reference scenario (REF). This emphasises the fact that this sector needs more strict regulations than just high carbon taxes, mostly due to the particularity of the decision making of consumers in this sector. The assumed carbon taxes in the supply sector seem to be enough for an almost full decarbonisation of the sector by 2060. In order to make that happen energy cooperatives should mobilise their financial power for investments in onshore wind and ground-mounted photovoltaic more than in the reference scenario (REF). Although imposition of high carbon taxes without any other regulations shifts the energy system towards a greater decarbonisation, it is still not enough for a full decarbonisation in all sectors such as the transport sector. Due to a partial shift from fossil fuels to electricity on the demand side to mitigate emissions, the potential of the prosumers for self-generation seems to fade what was seen in the reference scenario (REF) in the light of higher electricity demand.

The **carbon-free targets scenario (CFT)** explores the cost-optimal pathway towards decarbonisation by 2050 considering actors' behaviour. Decarbonisation requires a major shift in the types of energy carriers consumed and means a restructuring on the supply side as well as investments in carbon-free alternative technologies in the demand sectors. To achieve this objective, a shift from fossil fuels such as gas and transport fuels for energy consumption in the demand sectors towards more centralised energy supply sources, such as electricity, district heating and hydrogen, can be observed. This trend is accompanied with investment in decentralised energy sources, such as biomass consumption in industry for self-generation and in households for heating as well as an increase in the use of heat pumps based on ambient and geothermal heat in the household sector - which drives up the need for centralised electricity demand. The increased use of hydrogen by demand sectors greatly amplifies the electricity demand for the supply sector itself to produce hydrogen via electrolysis. Decarbonisation in the transport sector is only possible with a shift towards electric and hydrogen vehicles as well as increasing the use of public transport for local and national transport needs. The decarbonisation target also changes the energy supply landscape in that opportunities are opened up for a more diverse pallet of actors. While all energy suppliers invest in renewables, institutional suppliers dominate the use of onshore wind with utilities also take up a more significant role in this market with regard to offshore wind. Energy cooperatives favour ground-mounted PV, but also enter the onshore wind market more significantly. Overall, decarbonisation is only possible through the increased use of self-generation and decentralised sources, however this is also only possible through the hand-in-hand increased decarbonised generation of the supply sector, which needs to supplement consumption with an increased supply of electricity and the incorporation of hydrogen. Therefore, the energy system will show a mixture of centralised and decentralised elements.

Discussion and conclusions

The insights gained through the results show that the methodological extensions to improve the representation of actors in existing technology-rich energy system optimisation models will result in better assessment of supply and demand-side policy needs. The model coupling procedure performed within this study provides a holistic view of an integrated energy system in its entirety with enhanced representation of actors that facilitates policymakers to identify applicable innovative solutions to significantly reduce greenhouse gas (GHG) emissions in an economical and socially sustainable manner relevant to the various actors within the different sectors. This methodology also lends itself to advance the analysis of policy coordination challenges among related investor and consumer actors increasing consistency of modelling practices and their use in defining low-carbon transition pathways. These insights will be important for developing incentive schemes and market mechanisms fostering technology adoption. The framework is capable of targeting more sensitive investor actors and consumer actors and analysing how non-technological drivers and energy and emission targets can affect investment decisions and maximise cost-effectiveness of the energy system transition.

The results of the new **TAM model compared to the aggregated model** have shown that the common aggregated method applied towards energy planning can overestimate overall consumption as well as underestimate the overall emissions. Consequently, TAM results indicate that efforts in the industrial sector should be aimed at increasing the share of renewable energy sources in the energy mix by ensuring a reliable supply of biomass as well as deploying carbon capture technologies for industrial processes that cannot be further decarbonised due to process-related emissions. The household sector will require investments in the short to medium term aimed at ensuring participation and harnessing the potential of the rental sector, particularly in urban multi-family homes, where the greatest demand for heating and water heating resides and will profit from support for building insulation to reduce demand and financial and legislative support for heat pumps and solar thermal technologies to make these more attractive. Furthermore, the passenger transport sector is the most expensive sector to decarbonise not only due to costly infrastructure and fleet extensions but also due to consumer’s decision making behaviour which includes intangible costs such as travel time, adversely affecting the use of more efficient public transport means. Within the supply sector the onshore wind technology could be the overall main winner once cheaper capital especially from institutional investors are steered towards investments in this technology particularly in northern Germany. The untapped potential of some other renewable resources such as ground mounted PV, hydro and geothermal can be unlocked through deploying investments from non-conventional actors who are active on a local level. The utilities will have to continue their current role as the provider of the reserve capacity to ensure the security of supply and take on a complementing role for investing in renewables across all regions especially offshore wind in the north.

Overall, all sectors are able to decarbonise and reduce their **CO_2-equivalent emissions** with some sectors able to undertake efforts to a greater extent than others. In the reference scenario (REF), emissions are reduced by 66.3% in 2050 of overall sectoral reductions compared to 2015 with 96.3%, 44.7%, 74.6%, 58.1%, 19.1%, 77.1% and 34.8% in the supply, industry (process emissions), industry (energy emissions), households, transport (private), transport (public) and rest, respectively. Compared to the reference scenario (REF) in the same time period, the carbon tax scenario (CTX) decreases the emissions by an additional 11.0% while the carbon-free targets scenario (CFT) decreases the emissions by an additional 28.4%, which emphasises that a carbon tax alone will not sufficiently drive the reduction in demand and production of emissions. Emissions reductions in the harder to decarbonise sectors such as industry and transport are only possible with an overall reduction in demand and investment in CCS technologies in industry as well as shifting to different modes in transport and incorporating carbon-free fuels like hydrogen. It is essential to overcome the high upfront investment costs which needs to be supported by a different kind of policy instrument.

Overall, the objective of the scenario analysis is to assess the optimal distribution of centralised and decentralised energy technologies and this is measured through the overall **degree of decentralisation** in the energy system as the share of electricity self-generation in the demand sectors in total electricity generation throughout the whole system. A comparison of the self-generation of electricity across all sectors shows that in all scenarios rooftop PV plays the greatest role with the highest contributions coming from the household and other sectors (agriculture, commerce, freight transport). Without the pressure of eliminating carbon from the energy system as in the carbon-free targets (CFT) scenario, coal represents a constant source of self-generation in the industrial sector, whereas in the decarbonisation scenario the focus shifts to harness renewable industrial waste. Bioenergy and wind feature more in the decarbonisation scenario where carbon-free options are required to meet the targets. Comparing the overall degree of decentralisation in the demand sectors in 2050 highlights that decarbonisation is not necessarily achieved through a fully decentralised system as evidenced that the lowest share of decentralisation (24.2%) occurs in the carbon-free targets scenario

(CFT) and the highest (35.3%) in the reference scenario (REF), which indicates that the supply sector has a significant role to play towards ensuring decarbonisation targets are achieved. However, the reference scenario (REF) only generates 504.5 TWh electricity in comparison to the 760.8 TWh of the carbon-free targets scenario (CFT). Here, self-generation in the industrial sector remains reliant on fossil fuels, however the share of decentralisation observed is lower than in the reference scenario (REF) as a result of the higher carbon taxes limiting the cost-efficiency of such generation. Households show the same pattern with greater shares of decentralisation in the reference scenario (REF) which indicates that households participating in decarbonisation of the energy system as required by the carbon-free targets (CFT) scenario are dependent on carbon-free centralised energy sources such as electricity and district heating to meet targets. Additionally, transport suppliers should use the opportunity to generate electricity for their own consumption in the electric fleet. The results of the TAM model denote that they invest in local onshore wind technologies for the medium-term from 2025 to 2045. However, with the expected fall of PV generation costs below onshore wind generation costs in the long-term, they should gradually switch to ground mounted PV technologies after 2040. Increasing the shares of decentralised **self-generation** only works in conjunction with an increased reliance on centralised energy supply such as electricity and district heating.

TAM as an actor model, depicts the respective **decision-making behaviour** with regard to the investment in decentralised technologies and their use or the reaction to changes in residual load under the respective framework conditions. The modelling of German energy system serves to demonstrate the application potential of the newly developed TAM approach and the necessary framework conditions. With the help of the newly developed modelling tool questions about the importance of decentralisation potential and involvement of actors are addressed. Moreover, building renovation for the energy transition or a transport energy strategy are studied in detail. From this, the design options of a smart, **mixed centrally and decentrally oriented energy system** and its technological options can be derived with their economic, ecological and systemic potentials as well as social aspects.

The insights derived from this modelling methodology provide actor-specific **policy recommendations** and identify an applicable roadmap for decarbonising the energy system, which will have maximum chances to be effectively implemented across relevant actors. For example, industrial actors will respond differently to carbon taxes according to their unique production routes and investment options, with cases ranging from large changes as a result of carbon taxes to cases where the same taxes lead to minimal change. The greatest opportunity to transform the energy sector in the household sector is to harness opportunities for new investments that need to be made on the larger scale in the mid-term (2020-2040) when the majority of existing heating technologies come to the end of their lifetimes and will need to be replaced. The passenger transport is the most expensive sector to decarbonize since it will still rely heavily on private cars and needs forced mechanisms to meet the environmental targets. The transition in this sector will affect consumers from various income groups differently. Investing actors in the supply sector should adopt different investment portfolios considering their diverse characteristics. The portfolios should be tailored to the heterogeneous supply sector with respect to different technologies and varying regional renewable resources to make the transition happen at least system costs.

Transfer potential

The TIMES Actor Model facilitates consideration of different actors' characteristics, potentials and limitations in each sector and still within the framework of integrated energy system investigations thanks to the coupling approach. Therefore, on the one hand TAM can be used competently as a tool to inform policies aimed at overall energy system transitions also showing the impacts of these policies on an actors level. On the other hand, TAM can also be applied to study how policy scenarios targeted at specific actors within a particular energy sector can affect other sectors and the overall energy system. Since sector models in TAM are separate, they can be utilised for studies limited to one or several specific sectors as well.

1. Introduction

The Paris Agreement reached at the COP21 reinforced the need for an imminent transition towards a low carbon economy. Representatives from 195 nations agreed on a long-term goal to keep the global average temperature increase well below 2°C, highlighting the necessity to reduce global greenhouse gas emissions as soon as possible (UNFCCC 2015). The lock-in effect of past fossil fuel infrastructure investments made by industrialized nations has contributed to the escalation of greenhouse gas emissions (Parry et al. 2007).

The Energy Union aims at providing secure, affordable and sustainable energy to all European citizens (European Commission 2015). The European Commission proposed a Regulation on the Governance of the Energy Union, whose aims include ensuring the achievement of the EU's 2030 energy and climate targets (European Commission 2018). Moreover, the Green Deal aims at promoting Europe as the world's first climate-neutral continent (Leyen 2019). This accounts for the different ways and degree of contribution of different countries to the Energy Union strategy and Green Deal, allowing for alternative clean technologies to be promoted to reduce the emissions in many developed areas. This promotion might be expensive, since existing infrastructure must be upgraded or replaced forcing the actors of the energy system to make investment choices, while these decisions should increase or at least maintain their financial benefits.

By ratifying the landmark *energy transition* strategy (widely known as "Energiewende") in 2010, Germany is diligently seeking a transformation of its energy system to a low carbon, environmentally sound, reliable and affordable energy supply. In order to strengthen this strategy and ensure that Germany's international commitments under the Paris agreement are fulfilled, the German government adopted the *Climate Action Plan 2050* (Klimaschutzplan 2050) on 14 November 2016. This plan outlines measures by which Germany can meet its various national greenhouse gas emissions reduction goals through to 2050 with sectoral targets. These strategies and plans are continuously complemented by other measures and set targets, such as the nuclear and coal phase-out adopted in 2011 and 2019 respectively. All these aspirations are to be realized in a cost-effective as well as reliable manner as stipulated in Energiewende, which significantly complicates the decision making regarding both energy provision and consumption. In addition to the national debates and discussion around the climate change mitigation measures and targets, the German government informs the international community about its endeavour towards climate neutrality by 2050 as emphasized in the UN climate summit in 2019 (EURACTIV 9/24/2019).

Decarbonisation is a multi-dimensional, complex and mid-term process requiring structural shifts in energy supply and demand, where essential technological and behavioural changes in investment, operation and consumption patterns have strong interactions with the economy, society and the environment. The significant challenges faced in moving towards a long-term decarbonisation of the energy system include increased demand, technological, economic - and market - barriers, limits to efficient technologies, lack of available alternatives to fossil fuels and charging infrastructure for vehicles with alternative fuels, diversity of actors (e.g., electricity and heat providers, policymakers, consumers, local authorities), heterogeneity of actors' behaviour, linkages with the rest of the energy system and acceptance of specific technologies among the society. Effective policy-making requires the consideration of the interactions across these aspects.

The climate targets of the Paris agreement to limit global warming below 2°C requires active participation of energy supplier and consumer actors to integrate renewable energy into the system and use more energy efficient technologies. In today's electricity sector, the variety of generation technologies and their cost structures has become increasingly heterogeneous (Bauknecht et al. 2020). The anticipated decentralisation of energy supply makes the provision of reliable power supply more complex and thus a comprehensive analysis of the energy system to estimate the effects of the expected developments is indispensable. Technological changes through the investment in low-carbon technologies will be vital to achieving decarbonisation, but the social, economic and behavioural aspects are equally important in determining consumers' investment in renewable technologies or participation in energy efficiency to reduce the amount of fuel input or final service demand. While common technology-rich energy system optimisation models are powerful tools for analysing the least-cost decarbonisation pathways, they usually do not take different actors' investment and consumption patterns into consideration. Thus, they fail to capture the challenges arising from the economic abilities and expectations of the various actors determined by, for example, the socio-economic characteristics and financial expectations in the demand and supply side and the respective interactions. Therefore, models with this typical structure are not able to take into account the decentralisation of power and heat technologies since investments in decentralised technologies are quite often driven by socio-economic characteristics of diverse actors.

This project systematically investigate which shares of decentralised energy systems should be targeted to the overall system if the political goals set for Germany for climate protection and the development of renewable energy should be efficiently achieved and how the overall system should be made up of centralised and decentralised technologies in order to achieve the goals effectively. The project addresses the remaining question: how would an optimal mix of decentralised and centralised technologies look? The objective of this project is to obtain the cost-optimal configuration of decentralised and centralised power generation technologies according to the heterogeneous economic characteristics of diverse investor groups while still behaving economically rational and with perfect foresight taking into account improved representation of actors' investment-related characteristics, i.e., budget restrictions. Cost optimality is examined from the system point of view, meaning that the investment decisions of actors serve the system's optimum.

1.1. Background and the need for energy system models

Decentralisation trends and the use of smaller energy generation units are already evident in the current development of energy supply in Germany and Europe. The investment decisions made by consumers will determine the costs and level of engagement in the energy transition. Why centralised power plants, irrespective of the used technology, benefit from economy of scale, they still entail high absolute investment costs due to their technological structure (for an overview see Schröder et al. (2013)). This has an impact on the type of actors or organisations that can make such investments (Bauknecht et al. 2020). To reach the energy transition targets, the decentralised structures of power and heat generation are gaining importance. Decentralised power generation units are operated close to consumption and thus serve the needs of the immediate consumer. Sometimes the operator of the decentralised plant produces for its own needs while the excess amounts of energy can be fed into the transmission network, forming the so-called "Prosumer". With the ongoing digitalisation and the aim to further integrate consumers into the electricity system the role of consumers may become an active one (Bauknecht et al. 2020). Therefore, beside the crucial role of actors in the supply sector, consumers of energy are at the core of the energy transition and have a critical role to increase the efficient use of energy with sustainable technologies or to be prosumer by investing in small-scale decentralised electricity and heat generation thereby shaping the future structure of the energy system.

The setting of energy and climate targets, policies and strategies on the EU level is supported by comprehensive qualitative and quantitative analyses. Model-based analyses play a crucial role in determining the path for the energy transition, informing the European Commission, the member states and the general public of the possible impacts of such development pathways. To inform the policy-making process, relevant modelling tools need to cover all sectors of the economy. Energy system models have long been supporting the formulation of energy policy at EU level. For instance, the German government currently uses a variety of scenarios and studies to determine different pathways for the energy transition (BMU 2019a). As an example the BID3 is AFRY's power market dispatch model that uses mixed-integer linear programming (MILP) to optimise the dispatch of power stations and model market prices, capacity evolution and other important features of power markets. BID3 minimizes the system costs in a year subject to constraints while modelling all 8760 hours of the year. BID3 models power stations individually and provides the opportunity to account for varying renewables, demand-side management as well as hydro and pumped/battery storage. The BID3 model is also used by the German Grid Development Plan (NEP Strom), which provides the four main German transmission system operators (TSOs) with the expansion requirements of the German electricity grid over the next ten and at most 15 years.

The Energy-Environment-Economy-Engineering (E4) models are powerful tools developed for long-term energy planning and determining least-cost decarbonisation pathways (Chiodi et al. 2013; Føyn et al. 2011; Yang et al. 2015) by representing environmental, economic and technological dimensions of the integrated energy system. The bottom-up, technology-rich TIMES (The Integrated MARKAL-EFOM System) model generator belongs to the category of E4 optimisation models and is developed and maintained by the Energy Technology Systems Analysis Programme (ETSAP), a Technology Collaboration Programme of the International Energy Agency (IEA) (Loulou et al. 2016). Several energy system models have been developed using TIMES to represent the energy system from global (Loulou and Labriet 2008) to continental (Simoes et al. 2013b), Pan-European level (Kypreos et al. 2008), national (Balyk et al. 2019; Rosenberg et al. 2013; Haasz 2017b; Daly and Fais 2014; Balyk et al. 2019; Haasz 2017a) and regional (McCollum et al. 2017; Di Leo et al. 2015; Rühle 2013; McCollum et al. 2012) level to identify the least-cost pathways of the energy system. These family of models choose different technologies described with details on economic parameters (investment cost, fixed and variable operation and maintenance (O&M) cost, fuel costs and etc.), technical parameters (efficiency), environmental parameters (emissions), potentials of renewable resources and others through minimizing the global objective function representing total discounted system costs to fulfil demands considering a central decision maker (only a "system-wide" decision maker, with perfect information and foresight). However, most models represent energy systems by a few average actors representing large groups of consumers or producers and thus fail to incorporate the unique economic, technical and behavioural characteristics of the different players, which can consequently lead to achieving inaccurate results and hence unrealistic policy design. Due to the vast number and variety of consumer actors, an average actor could not accurately represent the heterogeneous socio-economic characteristics and diversity of micro-level decision making. In addition, the financial aspects of benefit-driven actors (supply sector, industry and providers of passenger transport) such as available budget for investment are overlooked resulting in overestimates of expected investments. In order to improve the actors' investment realism, it is necessary to take into account actors' heterogeneity with diversity (Cayla and Maïzi 2015) of characteristics and behaviour across different groups.

Despite the powerful representation of energy system, the E4 models suffer from the limited ability to fully evaluate the influence of behavioural changes on the energy system. Lind et al. (2017) have highlighted the importance of incorporating human behaviour into energy system models as it can affect energy efficiency measures implementation. E4 models that are currently used to assess and support energy and climate policies at national and EU level, do not fully integrate and represent the new challenges posed by the decentralisation and energy transition such as rational behavioural aspects. So, there is a need to enhance their capabilities in order to be able to analyse both policy implementation aspects and the design of long-term low-carbon transition more accurately. In order to model decentralisation for energy system planning process and better support policy-making, the concept of this project is built around the recognition of current gaps in decision support tools and aimed at improving the representation of both supplier and consumer actors in energy system modelling to investigate the optimum share of decentralised technologies.

1.2. Review of relevant work

Decentralising energy systems, infrastructure and networks can be regarded as an essential element of low carbon transition (Goldthau 2014). Therefore, many scientists have researched different aspects of decentralisation potential. For instance, Lilliestam and Hanger (2016) have examined the storylines of the two organisations (actors), to provide brief and comprehensible summaries of their visions towards decentralisation of electricity generation. The work concluded that the reason for this controversy among renewables proponents lies not in technology or cost, and can thus not be identified or resolved through techno-economic analysis or modelling, but in irreconcilable differences in normative aims and governance choices. Kubli and Ulli-Beer (2016) have investigated the interplaying effect of different network effects in the decentralisation dynamics of distributed generation concepts by means of a System Dynamics simulation framework. They have argued that the decentralisation dynamics of energy systems provide a unique opportunity to analyse the transition processes, as there is clearly one current dominating concept: the standard consumption model of the grid consumer. Schmid et al. (2016) have argued that the low-carbon energy system transformations are usually seen from a technical perspective and the decisive societal dimensions of actors and institutions are widely neglected. Therefore, in order to model decentralisation in energy system modelling practice, it is essential to improve the representation of actors. The methodological extensions in the developed TAM in this study is a step towards improving the representation of both consumer and supplier actors in industry, residential, passenger transport and supply sector.

Bauknecht et al. (2020) defined that the decentralisation of the electricity sector is mainly associated with the shift from an electricity generation in large power plants to a generation of mainly renewable electricity in smaller plants. They proposed a framework for assessing a decentralised electricity infrastructure considering four technological dimensions and investigated how these dimensions affect the costs of the energy system and the potential for participation. The dimensions are namely: (1) connectivity: the grid level of power plants; (2) proximity: the geographical distribution of power plants; (3) flexibility: options like storage and demand-side management (DSM); and (4) controllability: the coordination of generation and consumption. However, the final answer about whether centralised or decentralised electricity systems are preferable are not provided in their work. It only highlights the range of dimensions that need to be considered when discussing future decentralised electricity scenarios or making policy decisions.

Funcke and Bauknecht (2016) have developed a typology of (de)centralisation that distinguishes between (1) infrastructure location (connectivity and proximity), and (2) infrastructure operation (flexibility and controllability) focusing on the key techno-economic dimensions of the electricity infrastructure. They have argued that the introduction of feed-in tariffs (FiT) spurred this development as it allowed new actors with less financial resources to invest in generation. This is due to the design of FiTs, which guarantees a calculable remuneration for the electricity produced by smaller-scale and less capital-intensive renewable energies based power plants.

Decentralised options and actors' rational behaviour have so far been simplified in energy system analysis. Central technologies have classic advantages in terms of efficiency due to economies of scale; decentralised technologies allow the deployment of smaller renewable and Combined Heat and Power (CHP) potentials and often have higher acceptance. In order to investigate the decentralisation potential of the energy system, it is necessary to identify actors and include their rational investment behaviour. Recently, several researchers have attempted to improve the representation of consumers' heterogeneity and incorporate behavioural aspects of actors in energy system models using different approaches. For instance, Ahanchian and Biona (2017) developed an exogenous behavioural model describing technology diffusion using an agent-based modelling approach and proposed to couple this model with the LEAP energy system model. Similar to this approach, Ahanchian et al. (2019a) have developed an agent-based model analysing modal shift potentials to be soft-linked with TIMES-DK. In addition, Fragnière et al. (2017) developed a hybrid model coupling a bottom-up and a top-down model and introduced artificial constraints to mimic approximately irrational behaviours. An alternative approach to include economic rational behavioural aspects in energy system models is an extension of the methodological approach to improve the representation of behavioural aspects and incorporate heterogeneity endogenously in energy system models. From an energy system modelling perspective, incorporating heterogeneity consists of dividing producers and consumers into groups characterised by their different rational attitudes and preferences. The rest of this section reviews the relevant literature with regards to representation of actors in industry, residential, transport and supply sector respectively.

In 2010, the industrial sector in European Union accounted for almost a quarter of total final energy consumption (Eurostat 2017). Due to this significant share, the industrial sector is represented in most of the energy system models. However, Wiese and Baldini (2018) argued that models of this type often represent and simulate industry in an aggregate way, neglecting the complexity of the different industry branches or the structure of the processes with regard to input fuels and potentials to abate emissions. Consequently, analyses based on these models can sometimes fail to report correctly the impacts of changes in the industry sector and can lead to misleading results, both in terms of policy design and energy system operation and planning. Bataille et al. (2018) also emphasized the challenge of decarbonisation of heavy industry due to its heterogeneity.

In light of these problematic issues, recently few researchers have attempted to improve the representation of the industry sector in bottom-up energy system models (Fais et al. 2016). For instance, Wiese and Baldini (2018) have proposed an enhanced version of industry modelling within Balmorel (Wiese et al. 2018) energy system model, aiming at adequately model heterogeneity in the sector and integrate it in established bottom-up energy system models. Their work focuses on detailed characteristics of the sector while still considering the connections to the electricity and heat supply system. Fais et al. (2016) have evaluated the critical contribution of the industry sector to long-term decarbonisation, efficiency and renewable energy policy targets in a more disaggregated and process-oriented manner. The methodology incorporates process-oriented modelling approach based on a comprehensive technology database for the industry sector in a national energy system model for the United Kingdom (UKTM), allowing quantification of the role of both decarbonisation of upstream energy vectors and of mitigation options in the industrial sub-categories. The energy-intensive industry sectors iron & steel, cement and paper are modelled in a process-oriented manner, meaning that the actual production processes are represented in the model. Balyk et al. (2019) have also modelled the industrial energy service demands at a very disaggregated level including twelve different subsectors in TIMES-DK.

Fleiter et al. (2018) have developed a methodology within a bottom-up energy model, called FORECAST, which includes a broad range of mitigation options combined with a high level of technological detail such as representing energy-using equipment and processes to reflect the heterogeneity in industry sector. Moreover, to consider heterogeneity among companies (different levels of energy efficiency, varying energy prices, number of employees, etc.), a distribution of payback time expectations is used. Li et al. (2016) demonstrated the integration of institutional perspectives on energy system transitions into formal energy economic modelling through quantifying the socio-technical narratives of stakeholders.

Despite the significant contributions of the mentioned studies, methodological improvements in the industry model developed in the current study aim to provide a more accurate representation of the real-life investment options of the diverse actors by disaggregating industrial branches into different 'Actors Groups' according to company size and production route and implementing a higher level of technological representation based on data collected for individual production plants. To further characterise the 'Actor groups', different electricity prices based on electricity consumption levels are also considered.

Typically, the household sector in Germany is represented in modelling exercises as one homogeneously defined average household representing all households (BMWi 2018), which oversimplifies the situation and leads to one technology identified as the most cost-effective solution to meet a particular demand. An average household also does not adequately capture the observed technological diversity and the differences in investment decisions and consumption behaviour across different types of households and does not account for barriers to actual investment behaviour on the part of this sector. Regarding the household disaggregation methodology, there is a need to discern between the financial and decision-making ability of households to be able to meet the required investment demands leading to the achievement of sector-specific renewable energy and energy efficiency targets. A refinement of this sector is necessary to improve the accuracy of the decision-making behaviour of actors in particular to account for the financial ability of households to be able to afford to make optimal decisions, and to acknowledge the limitations in decision-making power for new investments in distinctly defined household actor groups (Dobbins In preparation).

Cayla and Maïzi (2015) differentiate between investment and consumption behaviour and describe the various aspects of behavioural economics that contribute to how differently categorised households consume energy. Alternatively, to account for varying purchasing behaviour or preferences, a discount rate is applied (Daly 2015; Jaccard 2015), or preferences can be expressed through intangible costs (Jaccard 2015), or results from external simulation models are used as input to optimisation models to gain insights about more realistic projections of technology transitions with e.g. discrete choice models (Daly 2015; Horne et al. 2005). Heterogeneity of a market segment has also been undertaken through disaggregation to better account for differences in consumption (Jaccard 2015; Tomaschek et al. 2012; Reveiu et al. 2015) with also income-specific technologies to allow for the differentiation in affordability of different household market segments (Tomaschek et al. 2012). Focussing on urban areas, Dias et al. (2019) have explored the optimal system for a municipal energy system by incorporating investment constraints for households to account for limitations in available budget.

With regards to the transport sector in this class of models, Venturini et al. (2019) recognized two main approaches to incorporate behaviourally realistic modal shift. One consists in linking the bottom-up E4 model with an external transport model that handles the behavioural features and determines modal shares (Waisman et al. 2013; Girod et al. 2012; Brand et al. 2012). The other approach endogenously assesses modal shift within an energy system model, by enlarging the traditional model structure to include transport-specific variables and transport infrastructure (Daly et al. 2014; Pye and Daly 2015; Tattini et al. 2018a; Tattini et al. 2018b). These studies attempted to identify the limits for the travel time that users are willing to spend for commuting, as well as the budget they are willing to commit to meet transport demand: Travel-Time Budget (TTB) and Travel-Money Budget (TMB) respectively (Schafer and Victor 2000). Schafer and Victor (2000) argued that typically people are willing to spend an average of 1.1 hour per day on commuting and devote only a small fraction of the households' total budget (approximately 3-5%, for households that do not own a personal car) to meet transport demand. When income increases, users shift to faster modes of transportation: wealthier societies have increased mobility levels (Schafer and Victor 2000) emphasising the necessity to incorporate socio-economic characteristics in energy system modelling.

Several researchers have recently attempted to improve the representation of consumers' heterogeneity and endogenise the choice of service demand technologies to avoid the so-called "winner-takes-all" effect that occurs quite often in such energy optimization models. For instance, Salvucci et al. (2018) and Tattini et al. (2018b) have improved the representation of consumers' diversity and introduced competition across different modes of transport to endogenise modal choice in the TIMES-DK model. In light of integrating these aspects in transport sector, McCollum et al. (2017) have developed an approach to improve the behavioural realism of global integrated assessment models applied to consumers' vehicle choice. The authors have disaggregated the vehicle technologies and added extra cost terms (so-called "disutility costs", "intangible costs", or "non-monetary costs") on top of the vehicle capital costs. Ramea et al. (2018) have developed a novel approach called COCHIN (COnsumer CHoice INtegration) to incorporate a consumer choice model within an Energy System Optimisation Model. The authors have disaggregated the end-use demand to accommodate observable differences across consumer groups, quantified non-monetary costs (disutility cost) and included them in an extended version of the vehicle technology database and disaggregated end-use groups further into "clones" and added random error terms to capture preference variation or unobservable differences. Tattini et al. (2018b) have developed an innovative methodology to endogenise modal choice in energy system models by incorporating variables related to the level-of-service (LoS) of modes and consumers' modal perception called MoCho-TIMES. The authors have introduced heterogeneity of modal perception and monetized intangible costs associated with different modes of transport. The monetary budget, travel time budget and transport infrastructure -representing capacity to accommodate the travel demand- have been incorporated in MoCho-TIMES. Moreover, the modal competition is regulated through a set of constraints limiting the maximal modal shares.

The methodological improvements in the passenger transport sector developed in the current study is innovative by considering both operation and investment decision of both consumer and provider actors. Combined with the household sector, the affordability of several income groups for investment decision to meet their electricity, heat and transport demands reflects more realistic households' investment decisions in an integrated energy system model.

Typical optimization approaches within the supply sector usually disregard actor diversity and local energy system differences and restrictions. These approaches assume a homogeneous supply sector consisting of one "average actor" representing various actor groups, which has unlimited access to all existing technologies. This "average actor" is assumed to be located in an "average environment" with free access to all available (renewable) resources throughout the system (e.g., a country) and can deliver its generated power or heat to meet demands located anywhere, thus failing to represent the heterogeneous economic and geographic reality of suppliers as well as consumers and might lead to inaccurate policy advice. Moreover, only a few national models represent the regional differences within the energy system of a single country like TIMES-Canada (Vaillancourt et al. 2014), the US FACETS (Wright and Kanudia 2014) and TIMES-DK (Balyk et al. 2019). These bottom-up technology-rich models with clear sectoral segregation and a fine level of temporal and spatial resolution provide valuable and profound insight into the energy system under various scenario analyses. Furthermore, there is a substantial number of optimization models focused on a national energy supply sector, especially power generation. For instance, (Park et al. 2016), (Amorim et al. 2014), (Kannan and Turton 2013) and (Soria et al. 2016) investigate decarbonisation pathways and the need for new investments in transmission capacities in South Korea, Portugal, Switzerland and brazil respectively using TIMES models. However, these studies do not consider regional differences and actor diversity within this sector.

The actors in the supply sector of the energy system are typically modelled aggregated assuming that these actors act perfectly rational and make investment decisions uniformly and homogeneously. However, further investigation and research shows that this superficial consideration does not reflect the realism of their investment decision-making process. For instance, Salm (2018) conducted an empirical survey including 52 professional representatives from institutional investors and utility companies to elaborate differences in the overall willingness to invest in the German renewable energy market. The results show that given full exposure to electricity price risk, incumbent utilities would facilitate projects at a 3.04% risk premium, whereas institutional investors demand 6.61%. Similarly, Helms et al. (2015) have developed a conceptual financial model to explain the diversity of cost of capital across different types of investors with different hurdle rates in the supply sector. Therefore, this heterogeneity leads to different investment valuations specifically with regards to renewable projects. To address this shortcoming in energy system modelling, García-Gusano et al. (2016) have introduced different hurdle rates in an energy system optimisation model using different scenarios in order to study the effect of different risk perception and investment evaluations on the development of the supply sector especially with regards to capital intensive renewables using the ETSAP-TIAM model. However, these different hurdle rates used are technology-specific and therefore do not include the investor’s specific cost of capital. In addition, the supply sector of the energy system is sometimes studied with greater focus to investigate the obstacles and opportunities regarding the decarbonisation pathways of the sector. Nijs et al.

(2015) have investigated the European power grid using a long-term optimisation model to examine the impact of the need for power transmission grid extension on the energy system considering Germany as a single node in the system emphasizing the need for considering grid issues in the German supply sector.

Given all the above studies, a need is perceived for considering the diverse investors (i.e. actors) in the German energy supply sector, while at the same time incorporating the different regional differences within the sector, particularly in terms of renewable potentials, as well as grid aspects, such as the investment costs of extending power transmission grid. In this way the heterogeneous optimal investment behaviour of the actors towards decentralisation in different regions within Germany could be captured and addressed further in designing policy instruments targeting the decarbonisation of the German supply sector. The supply sector module of this project provides a methodological approach to improve the representation of actors' diversity in the German supply sector with a focus on new investments in wind (onshore + offshore) and PV (rooftop + utility scale) technologies by citizens, institutional investors and utilities as well as taking into account the regional differences and grid aspects in order to more realistically capture the heterogeneity of investment decisions.

1.3. Definition of decentralisation

There are numerous definitions for the term "decentralisation" in the context of energy system analysis, each from a different aspect that suits the purpose of the interpreter and their analyses. Thus, there is no consensus on a truly unique and broadly inclusive definition for decentralisation. We argue that there is no such need to have a firm definition of decentralisation with regards to the energy systems since decentralisation is multi-dimensional and occurs at different levels as well as sectors. Any unique definition for decentralisation limits research and might eventually be violated by new studies on emerging aspects of decentralisation.

However, there is common opinion among the experts in this field that there is always a local dimension associated with decentralisation (Agora Energiewende 2017). The local aspect is not necessarily limited to the physical space and the concept of spatial distribution of energy systems. It rather refers to the locality that exists in a decentral energy system topology meaning that the (renewable) energy resources, their availability and costs are locally different, the form, level and affordability of energy consumption differ from consumer to consumer and finally the consumer preferences are not uniform. Therefore, the efficient energy system solutions are not uniform and could be tailored to local contexts.

Thus this is already evident that decentralisation is not only limited to energy provision. It is also about energy consumption. However, most of the literature are dedicated to decentralised energy provision, specifically power generation (Ringler et al.; Funcke and Bauknecht 2016; Kubli and Ulli-Beer 2016). Decentralisation with regards to power generation is usually defined as power generation in smaller but numerous units "connected directly to the distribution network or on the customer side of the meter" (Ackermann et al. 2001). According to this definition, decentralised power generation does not necessarily mean renewable generation as it is sometimes inaccurately perceived. Nonetheless, decentralised electricity systems are believed to be more innovative, because of the need for producers and operators to customize generation and distribution according to the local specifications (Goldthau 2014). Moreover, with regards to the intersection where decentralisation and renewable generation meet, Lilliestam and Hanger (2016) have analysed the controversy between two power generation structures, namely centrally regulated, large-scale imports of controllable concentrating solar power from the desert versus decentralised electricity supply and disempowering big utilities. These two structures seek the same ultimate goal of 100% renewable electricity generation and emission mitigation though through two different pathways suggesting that decentralisation is not equal to renewable generation and thus should not be set as a goal by itself for energy transition. The goal is an economically feasible decarbonisation of the energy system through renewable energy resources as well as efficiency improvements while the energy security is not undermined. If decentralisation can serve this aspiration, it is warmly welcomed and if not in some specific contexts then maybe a centralised solution should be adopted. Therefore, we believe that decentral and central systems could and should coexist and there should be an optimal degree of decentralisation in the energy system.

For the sake of a further elaboration we consider other sectors within the energy system. The passenger transport sector of the energy system is believed to be one of the most difficult sectors for decarbonising with regards to its nature and the predominance of fossil fuelled internal combustion cars (Ahanchian et al. 2019a). Most of the passenger transport demand in Germany is still met by private cars (Ecke et al. 2019) which might be considered as a decentral system since the energy demand for transportation is met by small and private units, namely cars, that exist right at the consumption side i.e. households. Given the current technological composition of the private cars fleet this decentral system is not a sustainable one. A solution for this could be a transition or a modal shift towards public transport which is more efficient and less complicated to decarbonise. Therefore, in this specific case a more central transport system might be environmentally more favourable. However, this might turn out be quite costly because of the infrastructure expansion costs or the population might react in an inert manner against such a big transition because of the individuals' time or comfort considerations. In that case the dominance of public transport, i.e. a central transport system, might prove unsuitable and a car fleet of mostly plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), fuel-cell electric vehicles (FCEVs), CNG and LPG cars, etc., i.e., a decentral transport system, becomes more viable. This will in turn affect the electricity supply system due to an increase in electrical demand which, in turn, might shift the optimal decentralisation degree of the power supply system. Increasing the number of BEVs in the passenger transport fleet provides an opportunity for households to use small-scale decentralised power generation units, i.e., rooftop PV to run the electric vehicle.

As another example we looked at the residential sector. A large share of energy demand from the households is used for space heating. There are two typologies for space heating with regards to decentralisation. On the one hand there are central heating systems in every house using natural gas, biomass, etc., which is actually in contrast to its name a decentral system because they are small but many heat generation systems right at the consumer side. On the other hand, there is district heating which provides many households with heat in a more centralised form. district heating could be run by waste heat from power plants or other processes, which is more energy efficient and therefore more sustainable than the house central heating systems which consume natural gas. Therefore, a more centralised district heating system by this definition is more sustainable. Nevertheless, it might seem infeasible to warm all houses even those which are remotely located by district heating due to the infrastructure expansion costs. A sustainable solution might be the electrification of space heating in houses using heat pumps which in turn causes an increase in the electrical demand of the residential sector once again changing the optimal decentralisation degree of the electricity supply system.

All above considered, we support that the term "decentralisation" should be analysed in each specific context differently. In some cases, decentralisation might serve sustainability whereas in some other cases a centralised system might be more feasible to be decarbonised. Finally, in order to address all above faces of decentralisation we adhere to this definition: Decentralisation generally means fulfilling the energy demand by small though many units which are located at the consumption side of the energy system.

1.4. Significance of the project

The energy system analysis should help to support knowledge-based and systematic decisions in energy policy and energy research with regards to technologies and infrastructures for energy supply, energy conversion and energy use. In order to address the objectives of this study, methodological extensions taking into account the diversity of actors and their decision-making behaviour are performed in industry, residential, passenger transport and supply sectors of the German energy system. The newly developed TIMES Actors Model (TAM) is a technology-rich, linear optimisation model that represents the entire energy system, from primary energy supply, through energy conversion, down to industrial, residential and passenger transport end-use sectors on a national level. This new approach analyses the decentralisation potential of the German energy system and the necessary framework conditions. The TAM approach shows how the individual decisions of the actors (households, large consumers, energy suppliers) affect the overall system. In addition to the techno-economic aspects, socio-economic characteristics, preferences and restrictions are integrated into the decision-making behaviour of the actors involved in order to show their relevance for the decentralisation potentials. For this purpose, coupling mechanism is developed reflecting the interplay between the actors in an integrated way. In addition to that, decentralised technologies are more intensively integrated in the energy system models and regional aspects are considered.

Overall, the competition of decentralised power generation technologies and end-use technological options to fulfil the demand is captured through considering not only technical, economic and environmental performance of technologies and national systemic renewable potentials, but also socio-economic characteristics and financial aspects of consumer and supplier actors to form a decentrally oriented energy system. In summary, the novelty of TAM is a) the enhancement of the representation of actors and their operation and investment decision-making behaviour for the sake of a more realistic assessment, b) investigation of the role of diverse actors in an integrated energy system model separately and c) departure from an ordinary system-wide decision-making assessment for a more detailed and sectoral evaluation, while covering the entire energy system at the same time. Therefore, TAM could be used as a decision support tool for investigating operation and investment decisions in the German energy sector with improved representation of actors under different scenarios.

1.5. Definition of actors and their heterogeneity in the German energy system

The overview of actors with the potential for decentralisation in different energy sectors of Germany is depicted in Figure 1.1. The industrial enterprises are important group of actors, characterised by a large number of different actors and thus divergent decision-making situations: large enterprises have different requirements and framework conditions than smaller companies. For the question of the decentralisation potential of the German energy system, households also have a significant role to play. It is important to understand the heterogeneity of socio-economic characteristics, the status quo of buildings type, urbanization, access to different end-use technologies and the diversity of decision-making situations in households and to simulate the resulting consequences of price signal changes as well as environmental policies for investments in energy-related goods and their use, and thus the final energy demand.

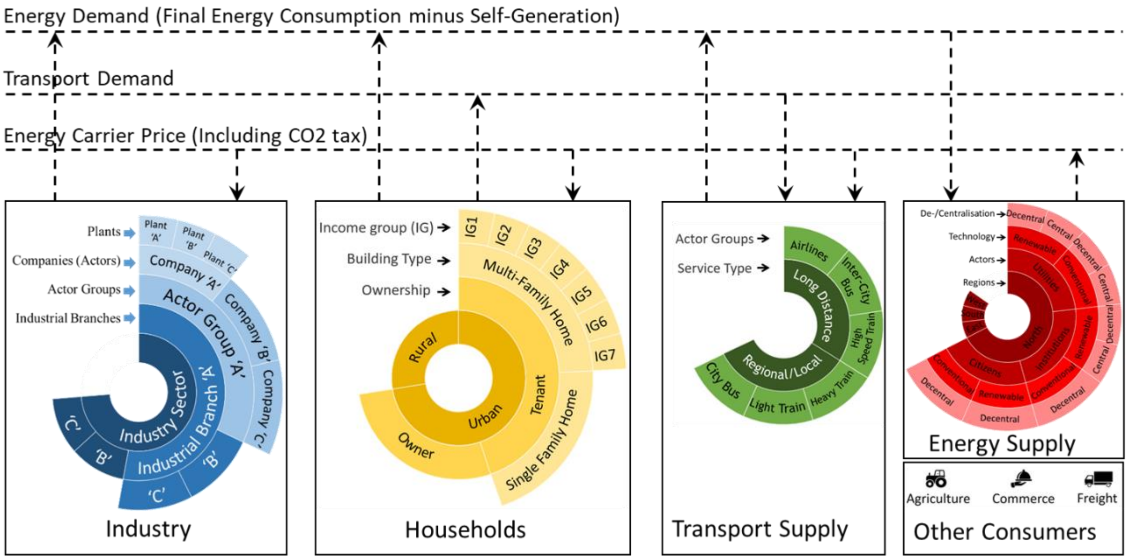


Figure 1.1: Overview of actors in different sectors

The consumers of passenger transport services are households while the providers of passenger transport services are disaggregated based on transport technology and the level of service. Within the supply sector and more specifically the electricity and heat sector, one of the most important factors which greatly affects the sector's decarbonisation is the uneven regional distribution of renewable potentials as well as the demand and the need for long range renewable electricity transmission. Moreover, there are also different actors in the supply sector which have different investment valuation and budget restrictions and therefore technology choices, which adds to the heterogeneity of this sector. TAM as an actor model, depicts the respective decision-making behaviour with regards to the investment in decentralised technologies and their use or the reaction to changes in residual load under the respective framework conditions.

1.6. Objectives and significance of the project

The objective of this research is to investigate the optimum share of centralised and decentralised energy technologies in the overall German energy system offering methodological extensions to enhance the representation of multiple heterogeneous actors to support the transition to a competitive, low-carbon energy system. The first step to include decentralisation in energy system models is to disaggregate the actors who play a role in the energy system. Then the heterogeneous financial and socio-economic characteristics of both supplier and consumer actors should be taken into account. To include these steps, methodological extensions are required aiming to improve the representation of actors in energy system models. In particular, the methodological improvements in this approach will:

- Determine the cost-optimal configuration of power and heat generation technologies according to the heterogeneous and realistic economic characteristics of diverse investor groups (actors) assuming economically rational investment behaviour.
- Improve the techno-economic characteristics of actors in each energy sector using separate individual sector models coupled together to find a new overall equilibrium so that the mutual impacts of the supply and demand sectors on each other could be investigated, while the sectoral insights are maintained.
- Highlight the least-cost solutions for different actors in the energy system so that policy-makers can better identify and target specific actors with policies and measures towards achieving the objectives of the energy transition.

1.7. Overview of German energy consumption and GHG emissions

Figure 1.2 presents the overview of sectoral final energy consumption and the respective environmental emissions. In 2018, the total final energy consumption in Germany was around 8417 PJ. The industry sector was responsible for 28.6% of the total final energy consumption followed by household (27.5%), transport (27.5%) and the other sectors (16.4%). Moreover, 905 million tonnes of CO_2 equivalent emissions were reported as the total GHG emissions of 2018 in Germany. The supply sector was responsible for the majority of these emissions with 36.2% followed by industry (21.3%), transport (18.9%) other sectors (13.5%) and households (10.1%).

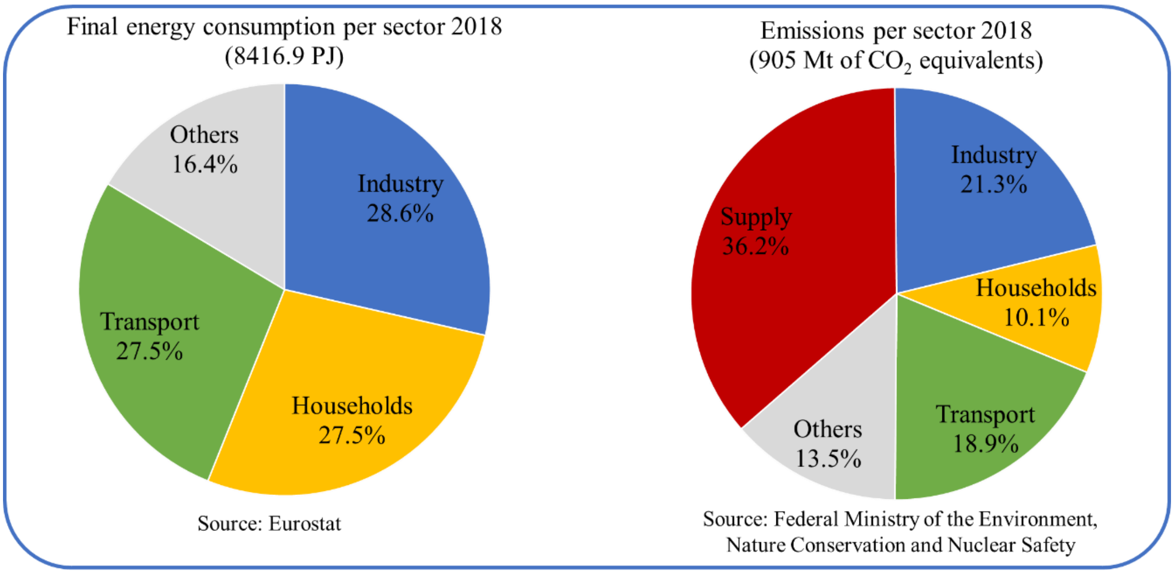


Figure 1.2: Final energy consumption and emissions by sector

In order to achieve a carbon neutral economy, all energy sectors should be decarbonised. Considering the sectoral emissions, it is evident that there is a substantial decarbonisation potential in the supply sector by large-scale deployment of renewable resources and emerging technologies such as carbon capture and storage (CCS), carbon capture and utilisation (CCU), power-to-X, etc. Nonetheless, this is extremely challenging without the contribution of the demand sectors. The demand side could participate with carbon neutral and efficient self-generation right at the consumption site, which will bring about a shift towards decentralisation of the total energy system. However, the decarbonisation pathways for each sector are different. Therefore, each sector should be separately analysed to discover their unique decarbonisation potentials, which contradicts the system-wide decision-making in current energy system modelling practice.

2. Methodology for the TIMES Actors Model (TAM)

Since Germany is a net importer of energy, there are some energy carriers which are mainly imported to the country especially the main consumed fossil fuels. These are crude oil and some other oil products such as naphtha and diesel, natural gas, hard coal, nuclear fuel, and electricity. The domestic prices of these energy carriers are set by their international prices at the German border with the addition of the mark-ups due to the further conversions and transportations within Germany. All sectors are calibrated to the base year 2013 and the modelling horizon is until 2060. Regarding time granularity, the modules are described at annual level, i.e., the models do not characterise intra-annual and intra-day variations. The spatial resolution of the model is on national scale covering entire Germany, with the exception of the supply sector consisting of four regions within Germany. Other consumers such as agriculture, commerce and freight transport are represented in a simplified way using the traditional modelling approach in TIMES family of models to have a full picture of the entire energy system. TAM is capable of analysing environmental pollutants such as CO_2, CH_4 and N_2O.

2.1. TIMES model generator[2]

TIMES (The Integrated MARKAL-EFOM System) is a techno-economic model generator for local, national, multi-regional, or global energy systems, which provides a technology-rich basis for representing energy dynamics over a multi-period time horizon. It is usually applied to the analysis of the entire energy sector, but may also be applied to study single sectors such as the electricity and district heat sector. Estimates of end-use energy service demands (e.g., car road travel; residential lighting; steam heat requirements in the paper industry; etc.) are provided by the user for each region to drive the reference scenario. In addition, the user provides estimates of the existing stocks of energy related equipment in all sectors, and the characteristics of available future technologies, as well as present and future sources of primary energy supply and their potentials.

Using these as inputs, the TIMES model aims to supply energy services at minimum global cost by simultaneously making decisions on equipment investment and operation; primary energy supply; and energy trade for each region. For example, if there is an increase in residential lighting energy service relative to the reference scenario (perhaps due to a decline in the cost of residential lighting, or due to a different assumption on GDP growth), either existing

[2] For more information refer to the TIMES documents (Loulou et al. 2016).

generation equipment must be used more intensively or new, possibly more efficient, equipment must be installed. The choice by the model of the generation equipment (type and fuel) is based on the analysis of the characteristics of alternative generation technologies, on the economics of the energy supply, and on environmental criteria. TIMES is thus a vertically integrated model of the entire extended energy system.

The scope of the model extends beyond purely energy-oriented issues, to the representation of environmental emissions, and perhaps materials, related to the energy system. In addition, the model is suited to the analysis of energy-environmental policies, which may be represented with accuracy thanks to the explicitness of the representation of technologies and fuels in all sectors. In TIMES the quantities and prices of the various commodities are in equilibrium, i.e. their prices and quantities in each time period are such that the suppliers produce exactly the quantities demanded by the consumers. This equilibrium has the property that the total economic surplus is maximized. However, since the TAM is a set of sector models, the equilibrium between the models are done exogenously through a model coupling using an iterative process. The internal equilibrium in sectors though takes place endogenously. Please refer to section 2.7 for more details.

The TIMES model is particularly suited to the exploration of possible energy futures based on contrasted scenarios. Scenarios, unlike forecasts, do not pre-suppose knowledge of the main drivers of the energy system. Instead, a scenario consists of a set of coherent assumptions about the future trajectories of these drivers, leading to a coherent organization of the system under study. In TIMES, a complete scenario consists of four types of inputs: energy service demand curves, primary resource supply curves, a policy setting, and the descriptions of a complete set of technologies, which are explained in details in the following sections.

TIMES uses linear-programming to produce a least-cost energy system, optimised according to a number of user constraint. Equation 2.1 shows the TIMES typical objective function to be minimized which constitutes of all costs discounted to a user selected reference year. The minimization is done over the modelling horizon, all time segments and all regions.

$$\sum_{r=1}^{R}\sum_{y\in YEARS}\sum_{t\in TS}(1+d_{r,y})^{REFYR-y} \times \left(Cap_{r,y,t}+Fom_{r,y,t}+Varom_{r,y,t}+Imp_{r,y,t}+Tax_{r,y,t} - Exp_{r,y,t}-Sub_{r,y,t}-Salv_{r,y,t}\right) \quad \text{Equation 2.1}$$

Where:

Cap	is the investment costs (required capital) for new technologies and processes;
Fom	is fixed operation and maintenance costs of technologies and processes;
Varom	is variable operation and maintenance costs of technologies and processes;
Imp	is import costs (incl. energy carrier and material);
Tax	is taxes on production/consumption of commodities;
Exp	is export revenues (incl. energy carrier and material);
Sub	is subsidies on production/consumption of commodities;
Salv	is salvage revenues at the end of technology lifetime or the modelling time horizon;
R	is the set of regions in the area of study;
$YEARS$	is the set of total milestone years in the modelling horizon;
TS	is the set of time segments within each year;
$REFYR$	is the user selected reference year to which all costs and revenues are discounted.

By default, TIMES assumes competitive markets for all commodities, unless the modeller voluntarily imposes regulatory or other constraints on some parts of the energy system, in which case the equilibrium is (partially) regulated. The result is a supply-demand equilibrium that maximises the net total surplus by minimising total costs as the dual objective. TIMES may however depart from perfectly competitive market assumptions by the introduction of user-defined explicit constraints, such as limits to technological penetration, constraints on emissions, exogenous oil price, etc. Market imperfections can also be introduced in the form of taxes, subsidies and hurdle rates as is discussed in the following chapters.

2.1.1. Implementation of different cost of capital (hurdle rates)

TIMES models typically compute a total net present value of the stream of annual costs for each region, discounted to a user selected reference year according to Loulou et al. (2016). as a simplified version of Equation 2.1. The regional discounted costs are aggregated into a single total cost, which constitutes the objective function to be minimized . The model optimises the entire system with a perfect foresight approach, meaning that the whole objective function, consisting of all discounted annual costs across the modelling horizon, is optimised at once.

$$Total\ discounted\ system\ costs = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} \times ANNCOST(r,y) \qquad \text{Equation 2.2}$$

Where:

R	is the set of regions in the area of study;
$YEARS$	is the set of total milestone years in the modelling horizon;
$REFYR$	is the reference year to which all costs/revenues are discounted;
$d_{r,y}$	is the global discount rate (in this study fixed across regions and years);
$ANNCOST(r,y)$	is the total annual cost in region r and year y.

The TIMES model provides the opportunity to set different hurdle rates for any technology using technology-specific discount rates. The technology-specific discount rate replaces the global discount rate in the TIMES objective function (shown in Equation 2.2) only for the cash flows of that specific technology like in Equation 2.3.

$$Total\ discounted\ system\ costs = \sum_{r=1}^{R}\sum_{y\in YEARS}\sum_{t\in TECHS}\left(1+d_{r,y,t}\right)^{REFYR-y}\times ANNCOST(r,y,t) \qquad \text{Equation 2.3}$$

Where:

$TECHS$	is the set of all existing technologies;
$d_{r,y,t}$	is the technology specific discount rate in region r, year y for technology t (in this study fixed across regions and years);
$ANNCOST(r,y,t)$	is the total annual costs for technology t in region r and year y.

Assuming there are A to Z different investors with different cost of capital and return on investments, the technologies, which are available to these n investors, should have their own hurdle rates distinct from the global TIMES hurdle rate. This reflects the actual actors diversity which replaces the inaccurate assumption of a global investor making decisions for the whole system existing in common modelling practice. Equation 2.4 shows the improved mathematical formulation of the objective function to be minimized, considering the actors disaggregation.

$$\begin{aligned} Total\ discounted\ system\ costs = &\sum_{r=1}^{R}\sum_{y\in YEARS}\Bigg(\sum_{t_A\in TECHS_A}\left(1+d_{r,y,t_A}\right)^{REFYR-y}\times ANNCOST(r,y,t_A) \\ &+\sum_{t_B\in TECHS_B}\left(1+d_{r,y,t_B}\right)^{REFYR-y}\times ANNCOST(r,y,t_B) \\ &+\cdots \\ &+\sum_{t_Z\in TECHS_Z}\left(1+d_{r,y,t_Z}\right)^{REFYR-y}\times ANNCOST(r,y,t_Z)\Bigg) \end{aligned} \qquad \text{Equation 2.4}$$

Where:

$TECHS_A$	is the set of all technologies available to actor A;
$TECHS_B$	is the set of all technologies available to actor B;
$TECHS_Z$	is the set of all technologies available for actor Z;
d_{r,y,t_A}	is the specific discount rate for actor A representing its cost of capital;
d_{r,y,t_B}	is the specific discount rate for actor B representing its cost of capital;
d_{r,y,t_Z}	is the specific discount rate for actor Z representing its cost of capital;
$ANNCOST(r,y,t_A)$	is the total annual costs of technologies of actor A in region r and year y;
$ANNCOST(r,y,t_B)$	is the total annual costs of technologies of actor B in region r and year y;
$ANNCOST(r,y,t_Z)$	is the total annual costs of technologies of actor Z in region r and year y;

2.1.2. Implementation of budget restrictions

Budget restrictions are also a key driving factor which limits investments in capital-intensive decarbonizing technologies by each actor group according to its financial capabilities. Therefore, in order to emulate this effect in a more realistic way, the budget restriction of the actors should be reflected in the model. The budget restrictions are implemented using a user constraint on each actor group. Equation 2.5 shows the mathematical formulation of the respective constraint in the optimization problem representing the budget restrictions for actor group A as an example.

$$\sum_{r=1}^{R}\sum_{y\in YEARS}\sum_{t\in TECHS_A} new\_cap_{r,y,t_A} \times inv\_cost_{r,y,t_A} \leq Budget_A \qquad \text{Equation 2.5}$$

Where:

new_cap_{r,y,t_A} is new capacity of a technology of actor A built in year y in region r;
inv_cost_{r,y,t_A} is the specific investment cost of the above (equal across regions/actors);
$Budget_A$ is the maximum yearly budget available to actor A (e.g. citizens);

2.2. Industry

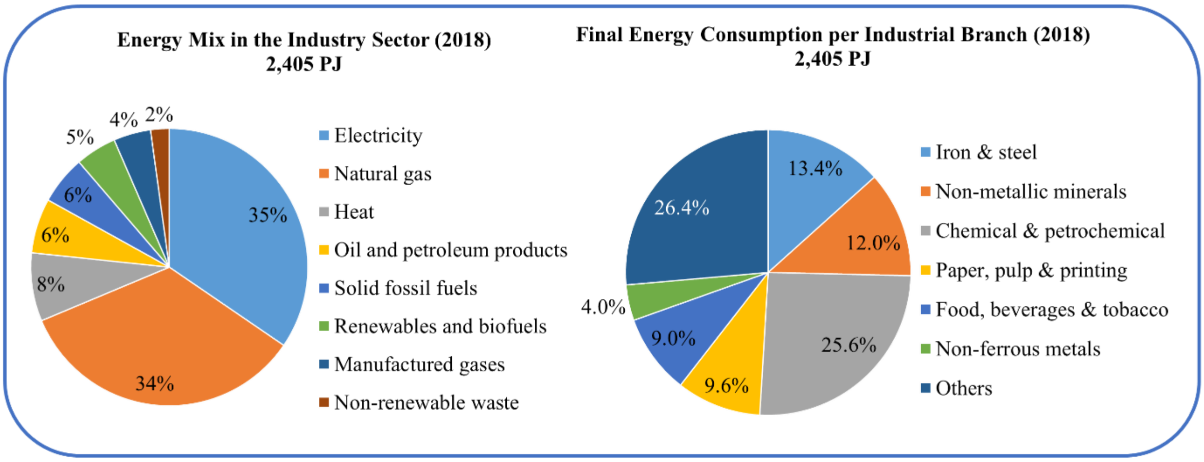


Figure 2.1: Overview of energy consumption in Industry

In 2018, the German industry accounted for approximately 29% of the total national final energy consumption (Eurostat 2017) and 21% of the total GHG emissions (BMU 2018). Electricity is the main energy carrier followed by fossil fuels, predominantly, natural gas (as seen in Figure 2.1.

With these shares, it plays a critical role in reaching the long-term environmental targets of the energy transition. For that reason, the German industry takes part in the European Emissions Trading System (EU ETS). Of all emissions traded in Germany, about 29% correspond to industry (DEHST 2019). However, the EU ETS alone is not enough to ensure sufficient emissions reductions in order to achieve the national targets of the energy transition.

In order to identify desirable pathways for the energy transition within the industrial sector, various energy system models have been developed. However, most models represent each branch of industry as a group of homogeneous actors. In reality, investment opportunities vary greatly between different actors within the same industry due to different production methods, capacities and plant age, to name just a few. By aggregating heterogeneous actors into a homogeneous group, the influence of different investment options of the unique actors is not taken into account. When it comes to the role of industry in the decentralisation of energy systems, such simplified, aggregated models are not sufficient to gain detailed insights for policy advice. It is therefore an essential part of this research project to increase the level of detail of the actors in order to take into account the differences in the respective framework conditions and investment opportunities.

The newly developed model for the actors of the German industry sector, called TAM-Industry, includes 14 industrial branches (13 defined industrial branches plus a 14th industrial branch that represents the rest of the industry) with special focus on the Iron and Steel, Cement, and Glass industries as shown in Table 2.1.

Table 2.1: Industrial Branches in TAM-Industry

Industrial Sector	**Represented in TAM-Industry**	**Share in Final Energy Consumption (%)**	**Focus**
Iron and Steel	*Iron & Steel*	*13.36*	*Yes*
Non-Metallic Minerals	*Cement*	*12.00*	*Yes*
	Glass (Hollow, Flat, Fibre, Special)		*Yes*
	Lime		No
	Other non-Metallic Minerals		No
Non-Ferrous Metals	Aluminium	4.05	No
	Copper		No
	Other non-Ferrous Metals		No
Chemical and Petrochemical	Ammonia	25.58	No
	Chlorine		No
	Other Chemicals		No
Food and Tobacco	Food & Tobacco	9.03	No
Paper, Pulp and Print	Pulp & Paper (High quality, Low Quality)	9.59	No
Other Industries	Rest of Industry	26.39	No

The applied methodology consists of three main parts. First, a bottom-up actor characterisation is performed with the aim of defining more representative “actor groups” regarding decision-making behaviour in the area of operation and investment in various production technologies as well as decentralised energy technologies. Second, the detail of technological representation of the existing productions status (based on the model’s base year 2013) as well as new technology investment options is expanded to better account for the unique characteristic of the different actor groups. In a third step, mark-ups for electricity prices are designated to each actor group according to consumption levels and implemented in the model. The next sections provide more insights into the steps mentioned above.

2.2.1. Disaggregation of actors

The approach in this package involves the bottom-up characterisation of actors for different industrial branches with the goal of defining 'actors groups' (see Figure 2.2) that better represent their decision-making behaviour regarding operation and investments in process technologies as well as decentralised technologies, under the respective framework conditions.

For this purpose, production data is collected for every plant for the year 2013 (see Figure 2.2). It is defined that a company constitutes an ‘actor’ in the industry sector. Therefore, plants belonging to the same company are aggregated together and considered as an actor (see Figure 2.2). Then, according to two main criteria, production technology and capacity (see Table 2.2), similar actors are grouped together to form 'actor groups' (see Figure 2.2).

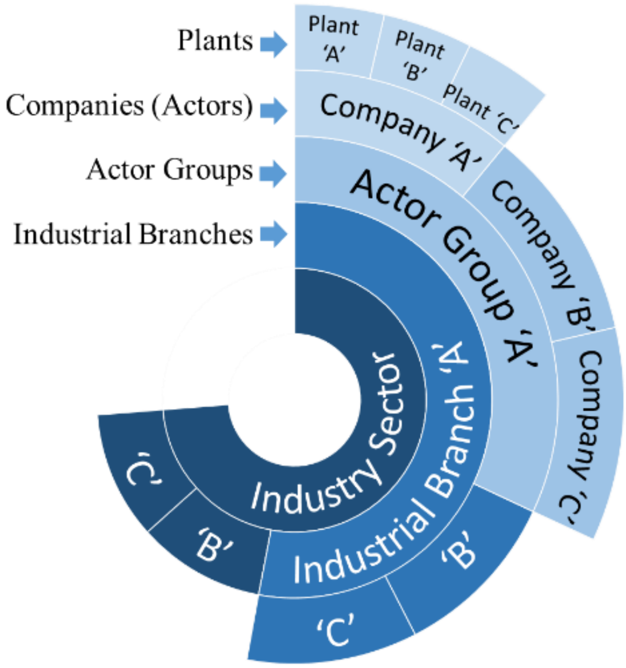


Figure 2.2: Representation of the different levels of disaggregation involved in the work

Table 2.2: Criteria used to characterise Actors

Criteria	**Relevance**
Production type/route	Production routes have a direct impact on the energy carries, energy demand and investment opportunities for process technologies and energy production
Production size	Production size has an impact on energy carrier prices

Using these criteria, actors in the Iron and Steel, Cement and Glass industries have been characterised and actor groups have been respectively defined.

As one of the most energy intensive and emission intensive industries, the Iron and Steel industry will be the focus of discussion in the following sections. The methodology improvements for glass and cement industry can be found on the appendix sections.

Case Study: Disaggregation of actors in Iron and Steel

Actors in the iron industry were aggregated into four representative 'actor groups'. Those companies that employ the Electric Arc Furnace method (EAF) were disaggregated by production size in two groups and actors that employ the Blast Oxygen Furnace method (BOS) method were divided into two in the same manner. Figure 2.3 shows the production outputs for actors in the iron and steel industry and their respective 'actor group' while Table 2.3 provides an overview of the resulting number of plants, companies and production that each 'actor group' represents.

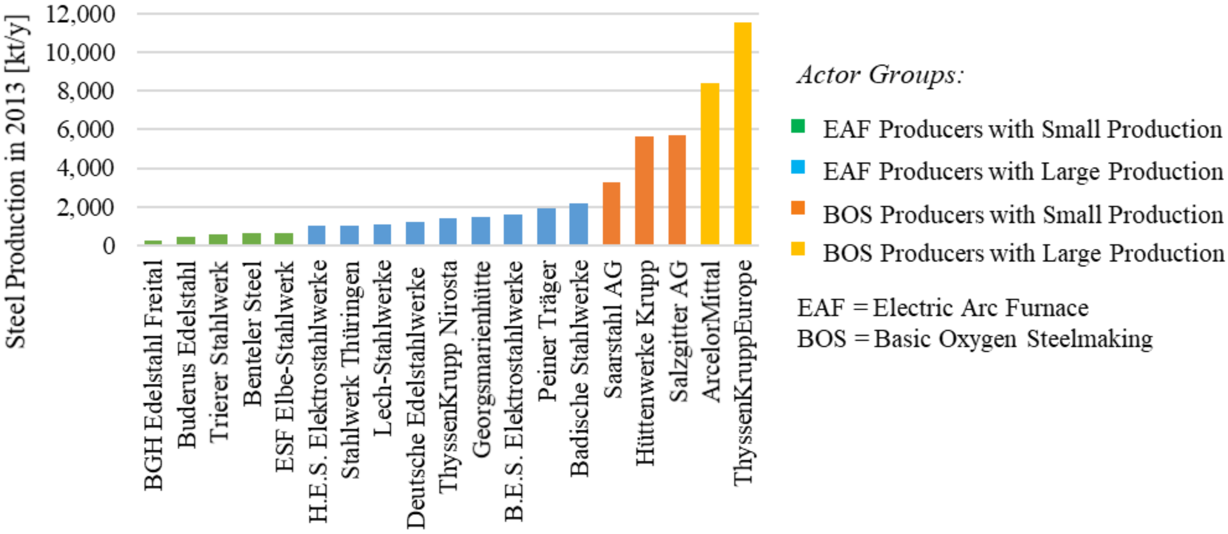


Figure 2.3: Characterisation of actors in the Iron & Steel production route and levels, 2013

Table 2.3: Iron and Steel Actor Characterisation based on 2013 Production

Production Route	Production Capacity	Group Name	Plants	Companies	Production (kt/year)	Share (%)
Electric Arc Furnace	Small	**SE**	6	5	1982	4.65
	Large	**LE**	19	9	10156	23.84
Basic Oxygen Furnace	Small	**SB**	16	4	13908	32.65
	Large	**LB**	10	2	16554	38.86
Total			51	20	42600	100

2.2.2. Conceptual methodological improvements in TAM-Industry

The starting point for the model disaggregation is based on the TIMES PanEU Germany model (Blesl et al. 2010). Here, the representation of processes in the base year is expanded to better capture the technological diversity of the existing industrial actors. For example, TIMES processes that represent a chain of processes in PanEU (see part a in Figure 2.4) are disaggregated and modelled individually (see part b in Figure 2.4). Moreover, the investment portfolio is expanded by implementing options for technology retrofits for base processes, best available technologies, innovative technologies identified to have high decarbonisation potential (including both industrial specific technologies and carbon capture and storage technologies) and self-generation technologies for electricity, heat and hydrogen.

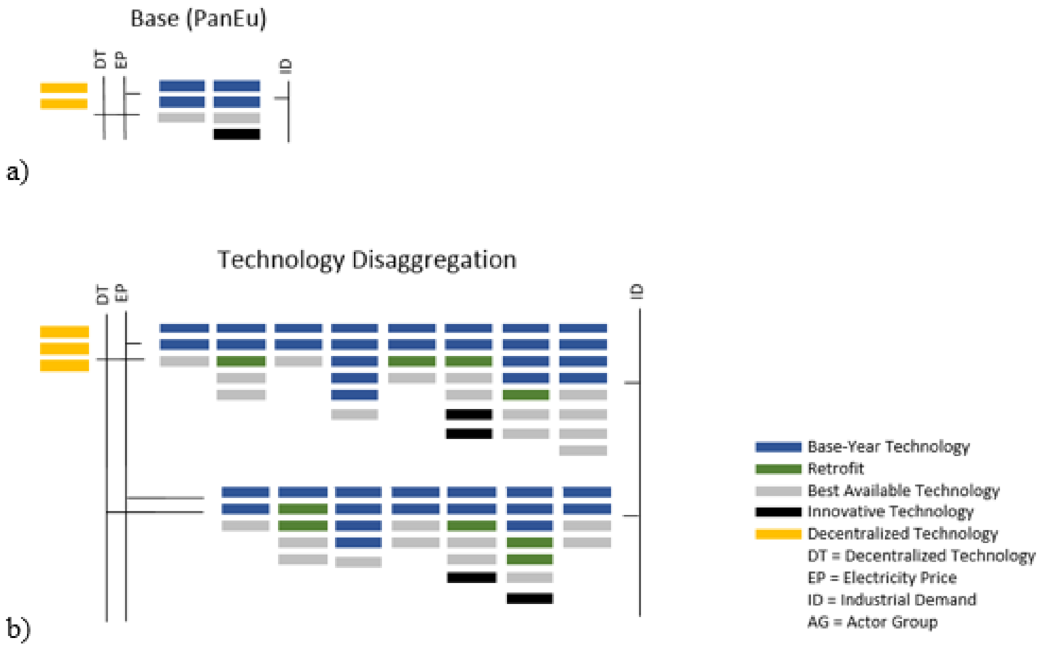


Figure 2.4: Simplified representation of Reference Energy System for TIMES PanEU and TAM-Industry with technological expansion

In a second step, each actor group is modelled and represented by a unique, independent production line that reflects the real production status of that group based on the data collected. For each of them, retrofit, best available and innovative technology and decentralised technologies investment options are implemented when suitable based on their current production status.

Additionally, as electricity prices vary depending on consumption level (e.g. higher consumption leads to lower prices), actor groups are assigned individual electricity price mark-ups accordingly.

Since electricity prices from the supply sector have an impact on the decision-making behaviour towards self-generation technologies, each actor group has its own self production technologies competing against electricity bought from the supply sector (at a price that incorporates the mark-up component) to properly assess their decentralisation potential. Figure 2.5 shows a simplified graphic representation of the model's topology after both technological expansion and actor disaggregation are implemented.

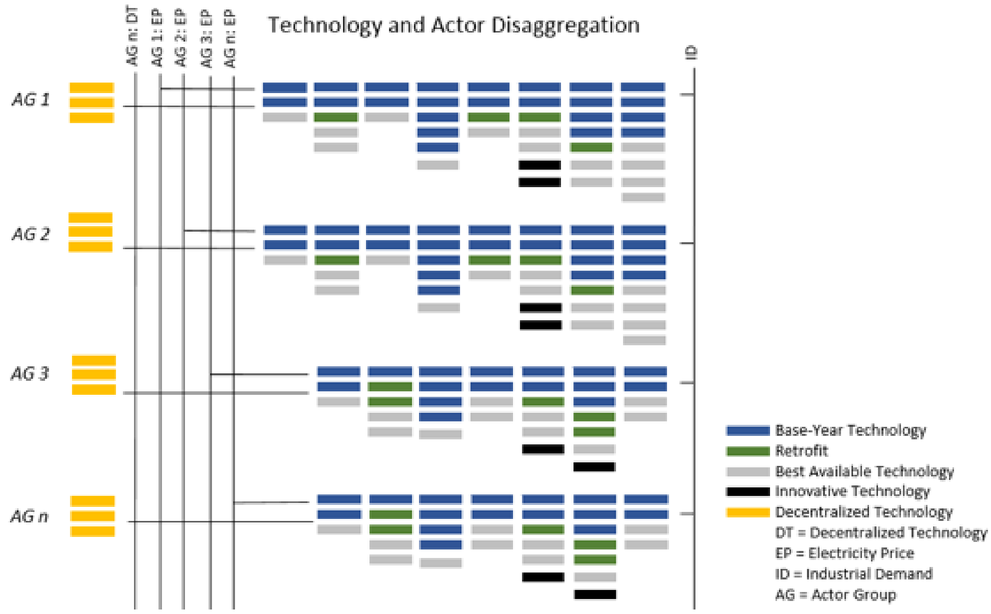


Figure 2.5: Simplified representation of Reference Energy System for TAM-Industry with technological expansion, actor disaggregation and different electricity prices

<u>*Case Study: Conceptual methodological improvements in TAM for the Iron and Steel Industry*</u>

The technical representation of the production of iron and steel is differentiated in two main routes, Basic Oxygen steelmaking (BOS) and electric arc furnace (EAF). BOS consists of 4 main processes; sinter, blast furnace, basic oxygen furnace and casting, whereas the EAF route consists of 2 main steps, the electric arc furnace casting. The following improvements were implemented in the model.

New Investments: Retrofits measures for Base Technologies: Options for investment in retrofit measures for process technologies with installed capacity in 2013 have been implemented in the model. Such measures result in the reduction of either electricity and/or fuel consumption. Table 2.4 shows the measures implemented and their corresponding savings per ton of steel produced.

Table 2.4: Retrofit measures and savings implemented in the TAM-Industry for Iron & Steel

Production Route	**Production Process**	**Retrofit Measures**	**Electricity Savings**	**Fuel Savings**	**Investment Costs**	**Lifetime**
			MJ/t_{steel}	**MJ/t_{steel}**	**EUR_{2013}/t_{steel}**	**years**
Basic Oxygen Steelmaking (BOS)	Sintering	Sinter cooler waste heat recovery	0	54	4.2	10
		Sintering waste gas heat utilization	38	51	5.2	20
		Partial sinter exhaust gas recirculation	-10	213	8.5	20
		Selective sintered exhaust gas recirculation power transformer	0	124	6.6	20
	Blast Furnace	Reduced blast gas losses	0	66	0.5	15
		Blast furnace waste heat recovery for process steam generation	70	0	3.3	15
		Bio-coal dust injection with 137,8 kg/t raw Iron	0	569	0	99
	Blast Oxygen Furnace	Converter gas recovery	0	750	38	10
		Target temperature control	18	0	0.6	20
Electric Arc Furnace (EAF)	Electric Arc Furnace	Foamed slag control	41	65	3.4	20
		Bottom flushing	70	0	1	20
		Evaporative cooling system	166	100	22.8	20
		In-site temperature measurements	108	0	1.7	20
BOS & EAF	Casting and Forming	Regenerative burners	0	408	6.2	10
		Recuperative burner	0	347	4.3	10
		Reinforced insulation of the furnace	2	160	17.2	20
		Flameless oxidation	0	396	4.3	10
		Cooling water waste heat recovery	-1	30	1.4	15

New Investments: ’Best Available Technologies/Measures’: The following best available technologies (BATs) and measures were identified and implemented in the model as shown in Table 2.5.

Table 2.5: Best Available Technologies/Measures for Iron & Steel

Production Route	Production Process	Best Available Technologies/Measures
Basic Oxygen Steelmaking (BOS)	Sintering	Sintering (State of the art) Selective sintered exhaust gas recirculation power transformer
	Blast Furnace	Blast Furnace (State of the art) Pellet Production Iron Cycle Converter Furnace
	Blast Oxygen Furnace	Blast Oxygen Furnace (State of the art):
Electric Arc Furnace (EAF)	Electric Arc Furnace	Electric Arc Furnace (State of the art): Electric Arc Furnace DRI Pellet Production
BOS & EAF	Casting and Forming	Casting and Forming (State of the art)
Alternative Routes		Ferro Chrome Smelting Furnace + Argon Oxygen Furnace Pellet Production + Iron COREX Cast Iron Cupola

As it has been identified that a shift from blast oxygen furnace to electric arc furnace could be a partial solution to the reduction of emissions in the iron and steel sector (Eurofer 2013), the blast oxygen furnace Actors Groups are given the option to invest in electric arc furnace technologies in the future. However, the electric arc furnace actor groups, are not given the option to shift production the other way around, that is, from the electric arc furnace to the blast oxygen furnace route.

Scrap availability is the main limiting factor for steel recycling and thus directly influences the extent to which the electric arc furnaces production route can be used and can be deployed. For 2013, it was assumed that 20 Mio. ton of scrap are available (Stahlinstitut VDEh 2017) and for the following years, a yearly growth rate of 0.9% was used (Eurofer 2013) (see Figure 2.6). Same assumptions regarding scarp availability were made for all scenarios.

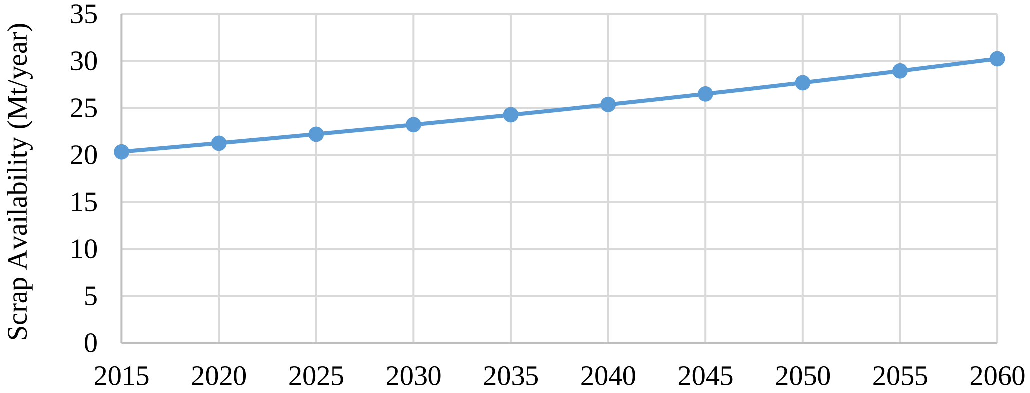


Figure 2.6: Development over the years of Scrap Availability in the Iron & Steel Industry

New Investments:' Innovative Technologies/Measures': The following innovative investment options for Iron and Steel production technologies identified to potentially play a key role in the future decarbonisation of the iron and steel industry (Schlemme and Achtelik 2018) were implemented in the model:

- *Primary steel production in the integrated steel mill with carbon capture and storage (CCS)*
- *Primary steel production in the integrated steel mill with carbon capture and usage CCU*
- *Primary steel production in the integrated steel works with top gas recycling (TGR-BF)*

New Investments: 'Decentralised Technologies': Regarding investments in decentralised energy production, the following technologies for Iron and steel production were considered:

- *Steam Electricity Generators*
- *Top-gas-pressure Recovery Turbine (TRT)*
- *CHP system*
- *Rooftop PV*
- *Biomass gasification for Hydrogen production*
- *Electrolysis for Hydrogen production*

Energy Carrier Prices: For German industrial consumers, prices in 2013 ranged from 15 ct/kWh to 5 ct/kWh according to the consumed amount of electricity (Faktenpapier Strompreise in Deutschland 2017). Thus, electricity consumption for each individual company was calculated to assign the corresponding price rates for each actor. A weighted average among all actors within an actor group was used. From this, mark-up prices were derived. The Actor group with the lowest electricity price served as reference with a mark-up of zero. The price difference from this baseline was then used as mark-ups for the other actor groups.

2.2.3. Calibration and Data

The TIMES-PanEU derived production line for the iron and steel industry uses the year 2010 for the base and calibration. However, 2013 has been set as the base-year for this project. Hence, an actualization of the baseline and recalibration of the model to 2013 has been performed. Calculations from data obtained from (Brunke and Blesl 2014) were used to calibrate installed capacities of the different production technologies and energy balances from Eurostat for the year 2013 were reproduced.

Development of the Market share of Actor Groups

Upper and lower bounds on the market share of the four actor groups are set. Each Actor group is allowed to increase their share of steel production linearly ranging from their current production share in 2013 to 100% of the Iron and steel demand by 2060. Equally, each Actor group is allowed to decrease their production linearly from their current production share to 0% of the demand by 2060. Setting these boundaries avoids one Actor group from suddenly taking 100% of the market share or suddenly disappearing while allowing any single Actor group to fulfil 100% of the Iron and Steel demand as well as fully lose their market share by 2060. An example for the case of Actor IIS4 (Blast Oxygen Furnace route, Large Producer) which holds a market share of 38.8% in 2013 is illustrated in Figure 2.7.

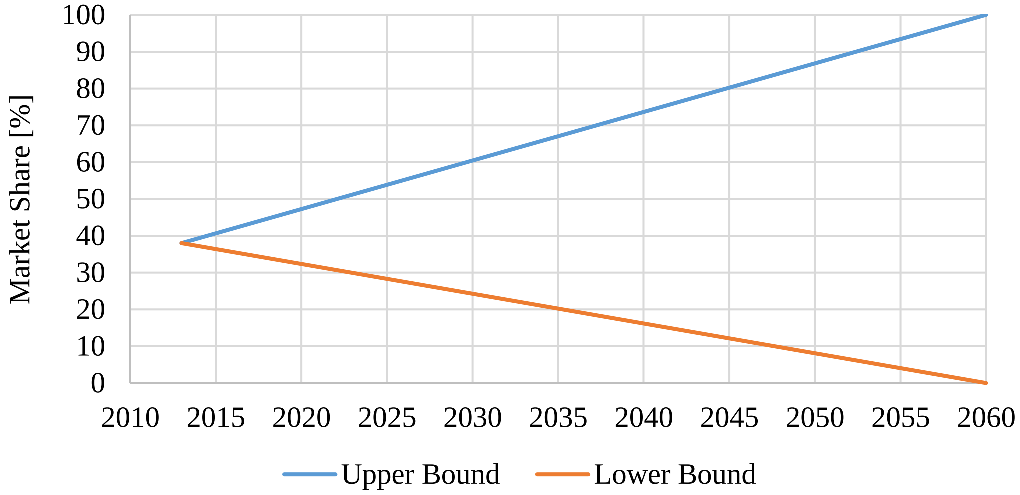


Figure 2.7: Upper and lower bounds on the development of the Market Share for the Actor Group IIS4

2.3. Households

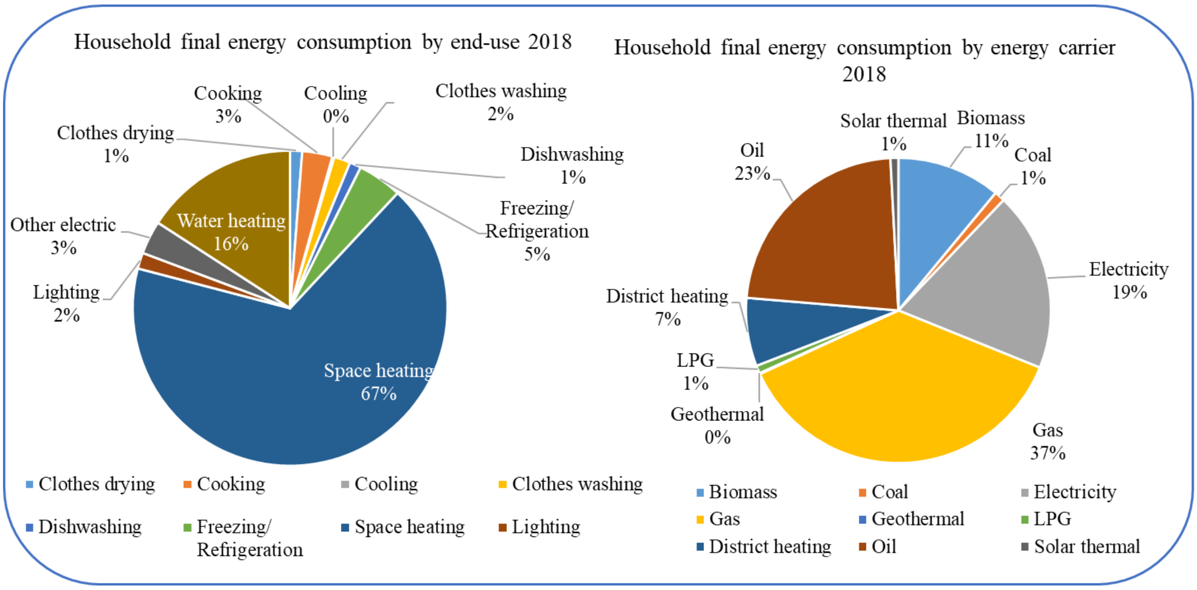


Figure 2.8: Overview of the fuel mix and end-uses in the German household sector

In 2018, households were responsible for 27.5% of the total final energy consumption, which corresponds to about 10.1% of the overall greenhouse gas emissions in Germany as shown in Figure 1.2 (BMU 2019a; AGEB 2019). The distribution of the consumption by energy carriers and end-uses is shown in Figure 2.8. The household sector has a significant role to play as it is becoming evident that without their active participation, the ambitious energy and climate change targets set by the government may remain unattainable. Households in Germany are expected to contribute to these targets by increasing shares of renewable energy use in heating (+14% by 2020), electricity (+≥35%) and transport (+10%), and decreasing energy consumption for heating (-20%), electricity (-10%) and transport (-10%) relative to 2008 (BMWi 2015).

However, current policy is based on modelling assessments which assume a homogenous population and monitoring benchmarks are calculated for average households and discounts the impact of the heterogeneity of this sector around acceptance, preferences, affordability, opportunities. While the residential and transport energy demands are typically modelled separately, they are actually a single decision maker. This type of simplification of analyses based on averaged actor groups leads to erroneous conclusions about the cost-optimal perspective of the types of technologies required to achieve specific targets and does not account for the affordability of specific actor groups. Furthermore, the investments in renewable or energy efficient appliances and energy retrofits for households are usually limited to an assessment of only the energy consumed within the home and excludes the holistic view of including transport energy investment and consumption decisions. Therefore, the analysis includes a link to the investment and energy consumption decisions for household passenger transport as far as these are related to decisions that household can take (see Section 2.4).

In order to improve the representation and analyse opportunities to reduce energy consumption and emissions and to harness the participation from households with decentralised energy options, this sector was disaggregated into specific profiles (defined by various characteristics described in the next section). These profiles take investment and consumption decisions better into account according to the specifics of the profiles as categorised allow for an analysis of the cost-optimal solutions for the overall energy sector as well as to each particular actor group. The overall household energy budget is considered by including this into the assessment for households as well as personal transportation needs. This additional disaggregation better reflects the holistic financial and decision-making power of specific actors in the household sector and is previously not reflected in modelling assessments for long-term energy planning in Germany. The investment limitations are represented with household budget constraints for each defined profile based on the available savings for each income group. This Total Investment Budget (TIB) commodity represents the statistically available savings for each income group. TIB is considered as the potential available budget that households could invest in more efficient or renewable-based end-use technologies (heating, water heating, lighting, other appliances), retrofit the building, small-scale PV rooftop power generation (playing a role as prosumer) and new transport technologies, e.g. conventional and electric bikes and cars.

2.3.1. Disaggregation of actors

The disaggregation of the heterogeneous actors within the household sector were categorised considering the major drivers of energy demand in the household sector, such as location, building type, appliances and standard of living (Frondel et al. 2018). To characterise the household sector in this study included establishing the distribution of the population and households for the base year 2013 into distinct profiles to account for socio-economic characteristics (and drivers of energy demand and ability to make investment decisions) such as income (disposable income, savings), household sizes (people per household), building type (single family and multi-family homes), building size (floor area), location (urban/rural) and tenure status. Furthermore, the energy consumption for each of these distinct profiles is defined based on the aforementioned classification criteria (Dobbins In preparation). In order to classify the households, an analysis of these various parameters was undertaken to disaggregate the households first by location, followed by ownership and building type, then income group as shown in Figure 2.9.

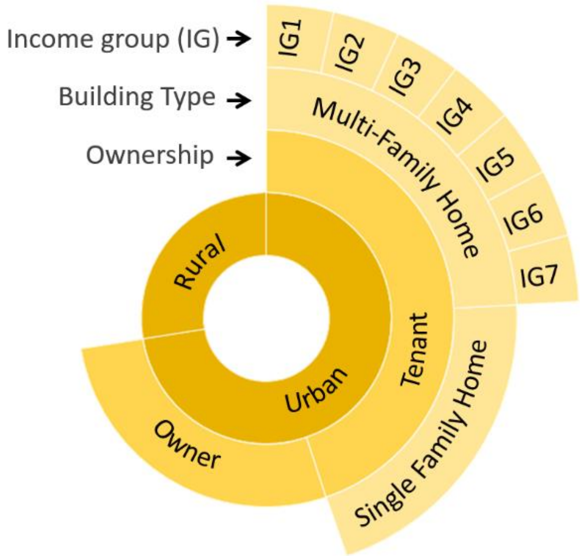


Figure 2.9: Classification of households by data parameters

Location

The location of households in 2013 is determined by applying statistically appropriate definitions to households in urban (corresponding to 76.9% of the population and 80.2% of households) and rural (corresponding to 23.1% of the population and 19.8% of households) areas (DESTATIS 2011).

Building type and ownership

The greatest potential for energy savings in the household sector lies in buildings, where the highest proportion of energy consumption is used for heating and hot water (AGEB 2019; Frondel et al. 2018; BMWi 2019; Kockat and Rohde 2012). One obstacle could be the ownership structure with regard to investments in decentralised energy supply systems. In 2013, 55.5 % of all inhabitants of Germany lived in rented apartments or houses. As a result, many households are not able to invest in energy savings related to the building envelope because they do not have decision-making power. Apart from ownership, the location is important because it influences the transport behaviour pattern and building type as well as the resulting energy demand and necessary technology investments or access to different energy sources. The building type influences whether one or more households would make a joint decision for decentralised energy systems. Given the distribution of households by income groups and the availability of other, relevant data parameters, the analysis was restricted to two types of buildings: single-family homes (SFH), accounting for 26.8% of all households, and multi-family homes (MFH), accounting for the remaining 73.2%. The profiles are further distinguished as owners (44.5%) or tenants (55.5%) resulting in an overall distribution of 23.6% of households as owners in SFH, 3.2% as tenants in SFH, 20.9% as owners in MFH and the majority of 52.3% as tenants in MFH (DESTATIS 2011, 2013).

Income group profiles

Without accounting for the income of households, the approach could underestimate the impact on lower income households and overestimate the possible contributions from the household sector towards achieving the overall objectives of the energy transition. Therefore, income is a key point of departure to better assess how households will invest in technologies and spend on energy costs and as such, the households were also disaggregated into specific income groups (as shown in Table 2.6) together with the building types and tenure.

Table 2.6: Overview of household sector by income groups

Monthly income per household (€)	**<900€**	**900-1500€**	**1500-2000€**	**2000-2600€**	**2600-3600€**	**3600-5000€**	**5000-18000€**	**Total/ Average**
Households (‘000s)	2,935	523	5,273	5,578	6,925	6,079	6,365	39,326
Population (‘000s)	2,935	19,659	7,910	10,040	15,235	15,805	19,095	78,851
Average monthly available income per household (€)	748	1274	1775	2327	3117	4302	7102	3130
Average monthly saving per household (€)	-139	-59.5	-18	39	162	445	1470	319

Accordingly, in 2013 the households in Germany (39.3 million households; 79.5 million people) were distributed with shares according to these characteristics (Table 2.7 and Table 2.8). The ownership ratio increases with increasing income.

Table 2.7: Characterisation and distribution of households in relation to income groups, 2013

Monthly income per household (€)	Urban				Rural				Total	SFH	MFH	Owner-occupier	Tenant
	SFH		MFH		SFH		MFH						
	Owner-occupier	Tenant	Owner-occupier	Tenant	Owner-occupier	Tenant	Owner-occupier	Tenant					
<900	4.4%	1.5%	7.4%	67.8%	1.2%	0.4%	1.9%	15.3%	100.0%	7.6%	92.4%	14.6%	85.4%
900-1300	7.9%	1.7%	11.4%	59.9%	2.2%	0.5%	2.9%	13.5%	100.0%	12.2%	87.8%	23.9%	76.1%
1300-1500	9.6%	1.8%	13.2%	56.1%	2.7%	0.5%	3.4%	12.7%	100.0%	14.6%	85.4%	28.3%	71.7%
1500-2000	12.0%	2.1%	15.2%	51.2%	3.4%	0.6%	3.9%	11.6%	100.0%	18.1%	81.9%	33.8%	66.2%
2000-2600	18.5%	2.6%	18.1%	41.0%	5.2%	0.7%	4.7%	9.3%	100.0%	27.0%	73.0%	45.7%	54.3%
2600-3600	20.5%	2.7%	18.7%	38.2%	5.8%	0.7%	4.8%	8.6%	100.0%	29.7%	70.3%	48.9%	51.1%
3600-5000	29.3%	3.2%	20.5%	26.6%	8.2%	0.9%	5.3%	6.0%	100.0%	41.6%	58.4%	62.6%	37.4%
5000-18000	27.2%	3.1%	19.2%	30.2%	7.6%	0.9%	4.9%	6.8%	100.0%	38.9%	61.1%	58.2%	41.8%

Table 2.8: Characterisation and distribution of households in Germany, 2013

Monthly income per household (€)	Urban				Rural				Total	SFH	MFH	Owner-occupier	Tenant
	SFH		MFH		SFH		MFH						
	Owner-occupier	Tenant	Owner-occupier	Tenant	Owner-occupier	Tenant	Owner-occupier	Tenant					
<900	0.3%	0.1%	0.6%	5.1%	0.1%	0.0%	0.1%	1.1%	7.5%	0.6%	6.9%	1.1%	6.3%
900-1300	0.8%	0.2%	1.2%	6.2%	0.2%	0.0%	0.3%	1.4%	10.3%	1.3%	9.0%	2.5%	7.8%
1300-1500	0.5%	0.1%	0.7%	3.0%	0.1%	0.0%	0.2%	0.7%	5.4%	0.8%	4.6%	1.6%	3.8%
1500-2000	1.6%	0.3%	2.0%	6.9%	0.5%	0.1%	0.5%	1.6%	13.4%	2.4%	11.0%	4.6%	8.8%
2000-2600	2.6%	0.4%	2.6%	5.8%	0.7%	0.1%	0.7%	1.3%	14.2%	3.8%	10.4%	6.6%	7.6%
2600-3600	3.6%	0.5%	3.3%	6.7%	1.0%	0.1%	0.8%	1.5%	17.6%	5.2%	12.4%	8.8%	8.9%
3600-5000	4.5%	0.5%	3.2%	4.1%	1.3%	0.1%	0.8%	0.9%	15.5%	6.4%	9.0%	9.8%	5.7%
5000-18000	4.4%	0.5%	3.1%	4.9%	1.2%	0.1%	0.8%	1.1%	16.2%	6.3%	9.9%	9.5%	6.6%
Total	18.5%	2.5%	16.6%	42.7%	5.2%	0.7%	4.3%	9.6%	100.0%	26.8%	73.2%	44.5%	55.5%
Urban / Rural	**80.2%**				**19.8%**								

The distribution of households according to type of building and ownership could be reliably distributed to income groups on the basis of the statisticians of the federal states and national statistics. Households with a monthly income of less than 900 € or between 5,000-18,000 € are 85% and 41% respectively in a tenancy. Furthermore, these distributions show that about 39% of households in the top income group live in a single-family house (EFH), 89.8 % of which are also its owners. In the lowest income group this figure is 7.6%, of which 74.8% are owners. About 93 % of the lowest income group live in multi-family houses (MFH), 10.1% of which are owners of owner-occupied flats. In the group with the highest income, 61.1% live in multi-family houses, 39.4% of which are owners. These are important findings for the expected investments of this sector as a contribution to the achievement of energy and climate targets, as the active participation of households is an important element in achieving the energy and climate targets.

Various data sets, such as those from Eurostat, Destatis, AGEB or DIW, and various studies are evaluated for the analysis. These different aspects mentioned above are plausibly assigned to the income groups on the basis of the data and literature and an energy balance is drawn up. In order to underpin the typology of households, an analysis of current energy expenditure and investments in the household sector is carried out, since it is in these sectors that the highest share of energy consumption is used for heating and hot water, and thus the greatest savings and contributions to the achievement of energy and climate objectives can be expected.

Figure 2.10 shows the shares of direct (operating costs) and indirect (investments) monthly energy expenditures of households in Germany in 2013. On average, households across all income groups spend 10% of their income on direct energy and mobility energy expenditures. However, higher income groups spend less on direct energy expenditures and more on indirect expenditures. This reflects the fact that higher-income households have more disposable income to spend on energy-efficient technologies, thus translating into savings on current energy expenditures. There are also differences in investment in household energy and mobility as a function of income. As income increases, more is spent on indirect energy investments (e.g. investments in household appliances or housing maintenance or improvement).

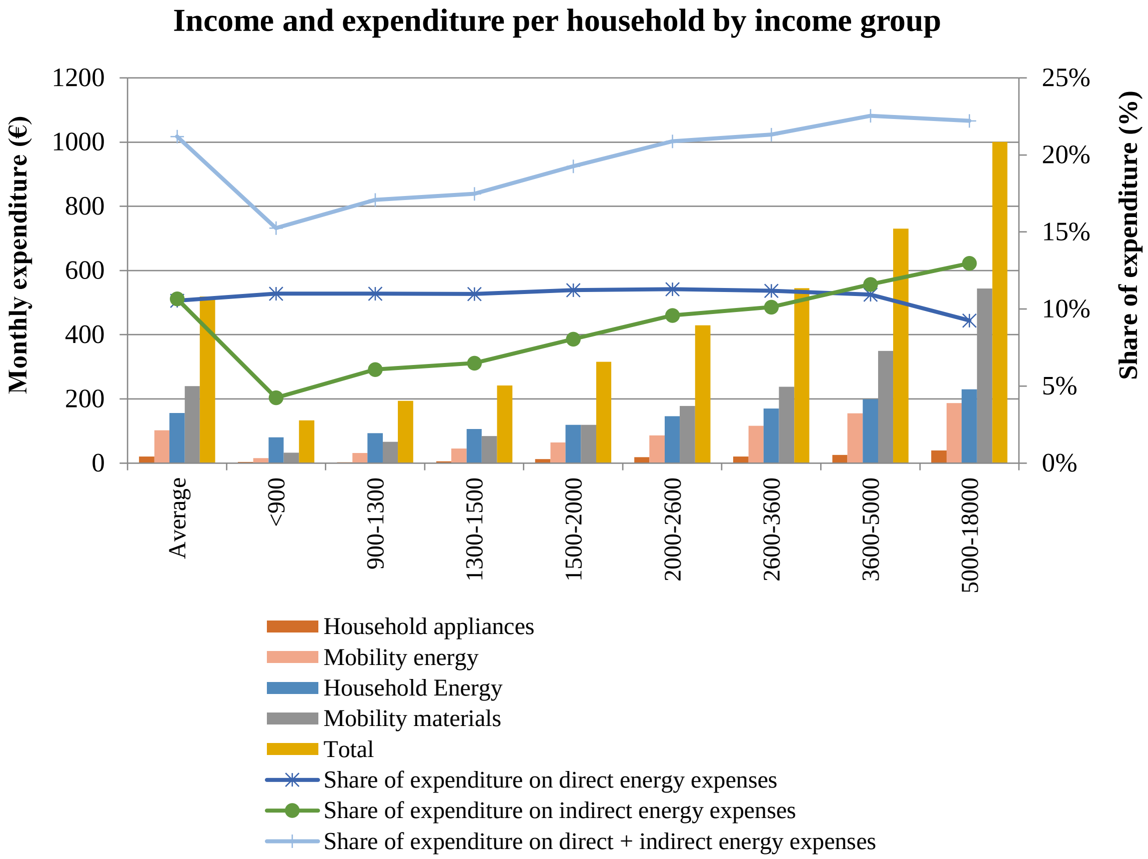


Figure 2.10: Income and expenditure per household by income group in Germany, 2013

Furthermore, the potential to afford high investment costs is examined by compiling the potential savings per income group. These are presented in Figure 2.11. It shows that less than half (45%) of all households save more than the average of all households (approx. 238€ per month), which could be considered available for possible investments in renewable energies and energy-efficient technologies. In addition, the decision-making power of households is also examined, and it turns out that 61.7% of the remaining households (45%) are homeowners, which corresponds to only 24.1% of all households and thus limits the prospect of possible investments.

Given the barriers to investment, strategies should be developed to tap into this potential. In order to develop such strategies, solutions are examined through an energy system model.

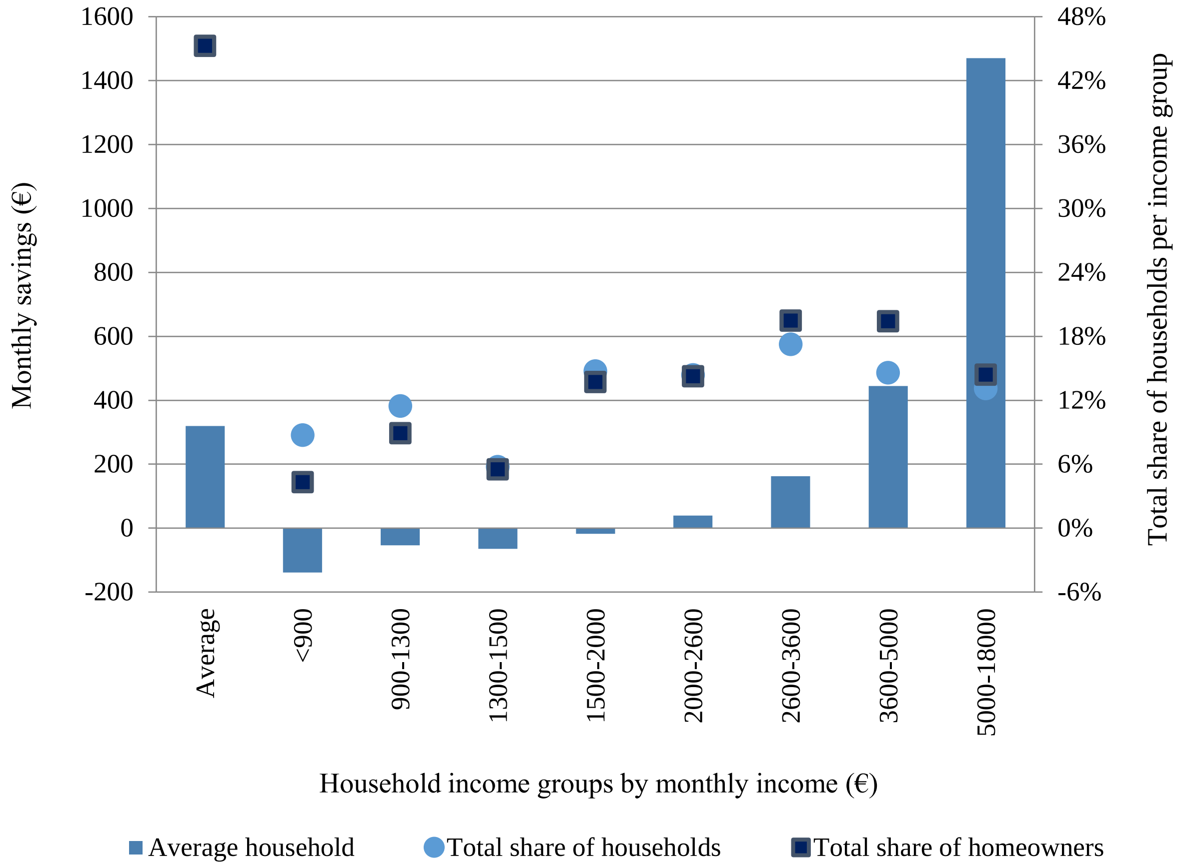


Figure 2.11: Potential of households to afford high investment costs according to available monthly savings by income group in Germany, 2013

2.3.2. Conceptual methodological improvements in TAM-Households

The basis for modelling households as actors is the actual investment and consumption behaviour of technologies by households in order to adequately capture and assess the social contexts. This is based on existing panel data, sample and case study analyses, from which preference and acceptance factors are derived. In addition, different types of households can be formed from these analyses, each of which reacts to the framework conditions (e.g., energy price level and structure, support mechanisms and regulatory requirements, income and education level) in its behaviour. These can be, for example, prosumers with a high proportion of their own generation (e.g., from decentralised PV systems) as well as the energy-poor households that are unable to pay their energy bills or to afford the high acquisition costs for energy-efficient appliances. For the different types of households, independent tools have been developed which, based on TIMES as an actor model, map the respective decision behaviour regarding the investment in decentralised technologies including their use and in energy efficiency measures under the respective framework conditions.

As described in Section 1.2, the household sector is typically represented in modelling exercises as one homogeneously defined average household to represent all households, which oversimplifies the situation and leads to one technology identified as the most cost-effective solution to meet a particular demand. Figure 2.12 depicts the representation of the household sector in the TIMES-D model, which is used as the basis for the aggregated model (Haasz 2017a). This includes defining building-specific demands for urban single-family house, multiple-family house, rural single-family home – each as an existing building and a newer more efficient building. The demands are defined as the total demand for the whole sector for cooking, lighting, freezer/refrigeration and appliances, and specific to the building type (urban SFH/MFH, existing/new, rural SFH, existing/new) for space heating, water heating and cooling.

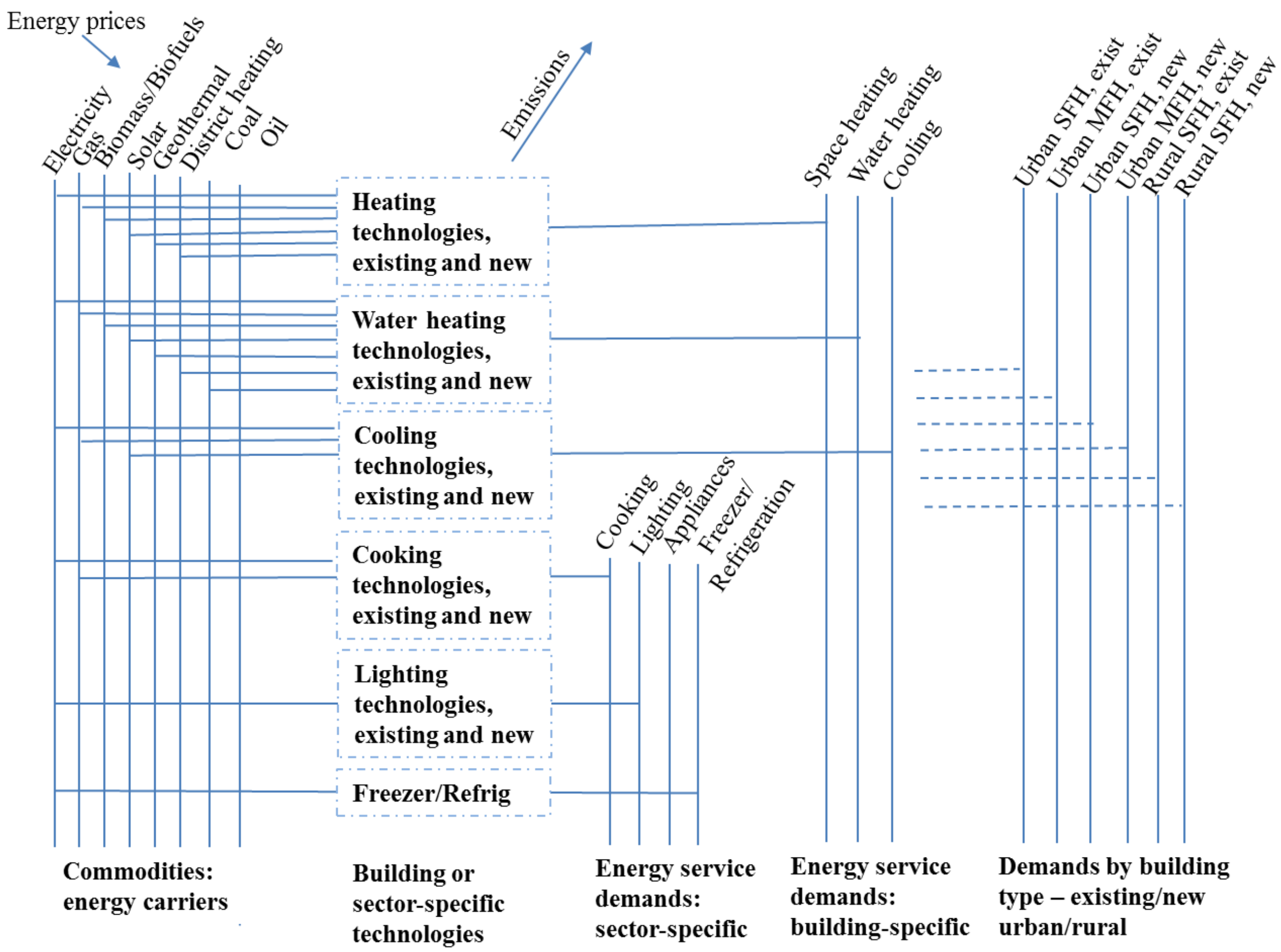
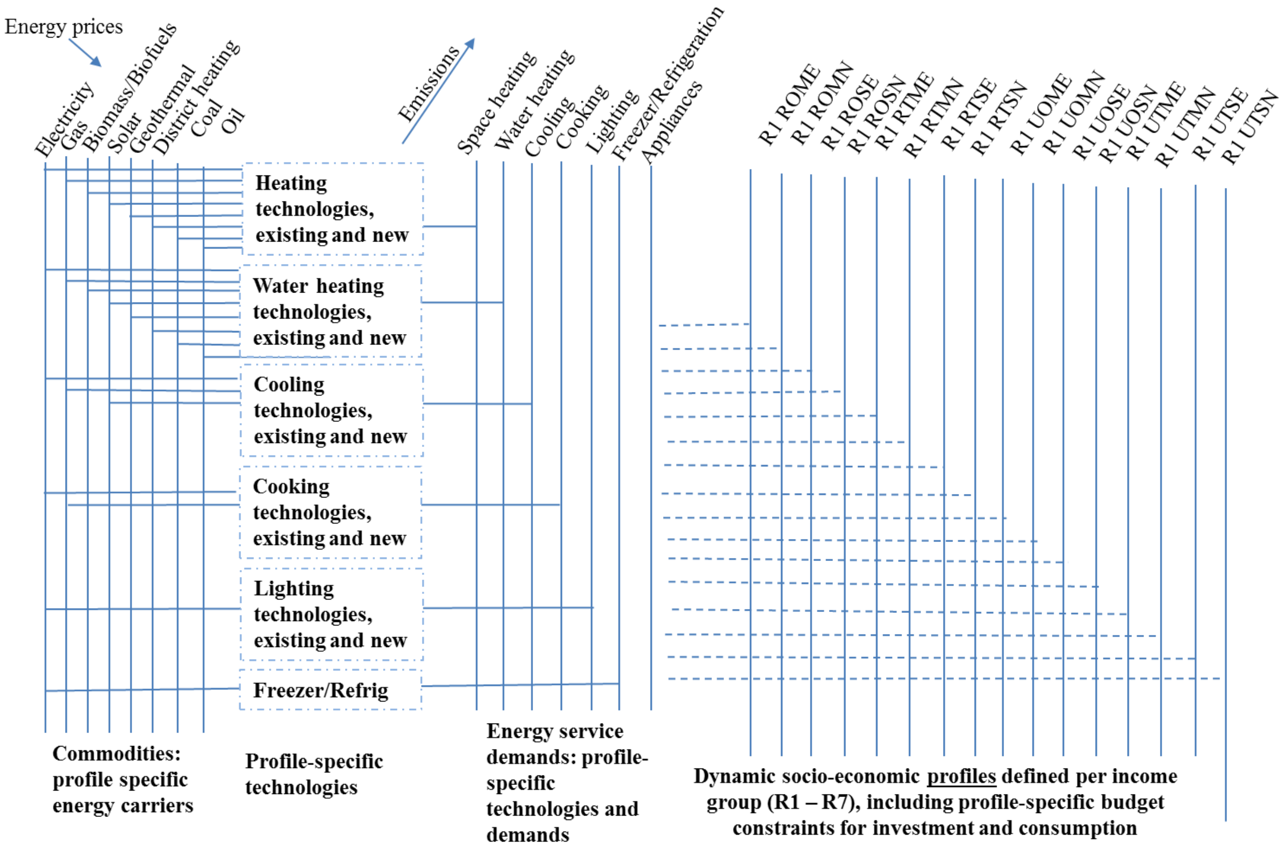


Figure 2.12: Reference Energy System for the common modelling approach with the aggregated model for the household sector

Since this average household also does not adequately capture the observed technological diversity and the differences in investment decisions and consumption behaviour across different types of households and does not account for barriers to actual investment behaviour on the part of this sector, a refinement of this sector is necessary to improve the accuracy of the decision-making behaviour of actors in particular to account for the financial ability of households to be able to afford to make optimal decisions, and to acknowledge the limitations in decision-making power for new investments in distinctly defined household actor groups (Dobbins In preparation).

This analysis is based on adapting the TIMES-D model by including a disaggregated representation of households into heterogeneous groups based on the socio-economic characteristics described in Section 2.3.1. The assessment includes both residential and personal transportation energy demand to comprehensively describe the impact on the total household energy. The model takes into account the limitations in available budget from the distinguished profiles through the implementation of profile-specific budget constraints, capacity constraints and discount rates. The budget constraints for each profile are calculated based on available statistics on income-specific typical investment in energy appliances, energy improvement investments and savings (DESTATIS 2013). The budget constraints for each profile are calculated based on available statistics on income-specific typical investment in energy appliances, energy improvement investments and savings (DESTATIS 2013). This better accounts for the gaps in investment from the different income groups and, in turn, assists in identifying insights for achievable targets and development of policy measures towards the improvement of the energy welfare of lower income households is explored.

As shown in Figure 2.13, the final model disaggregation includes income group, tenure status and building type specific profiles, energy service demands and technologies as well as profile-specific budget constraints for investment and consumption. The model is dynamic in that the population can shift into other income groups and buildings over time, thereby allowing a better representation of the shifts in energy demands based on the way people live.



LEGEND	R = Rural; U = Urban	M = MFH; S = SFH
R1-R7 = Income group disaggregation	O = Owner; T = Tenant	E = Existing; N = New

Figure 2.13: Reference Energy System for TAM-Households

2.3.3. Calibration and techno-economic assumptions

The disaggregate data in the model is calibrated using the final energy consumption statistics (BMWi 2019) and emissions (BMU 2019a) which details overall energy carriers by end-use for the household sector for the base year 2013 and calibrated to the projected market shares for the model year 2015 (BMU 2019b) as shown in Figure 2.14. The model exhibits differences in the total oil consumed in 2015 (+9%) due to the continued use of residual capacities and results in a higher demand for heating (+4%). The amount of oil consumed in the model in 2020 statistically matches projections (BMU 2019b).

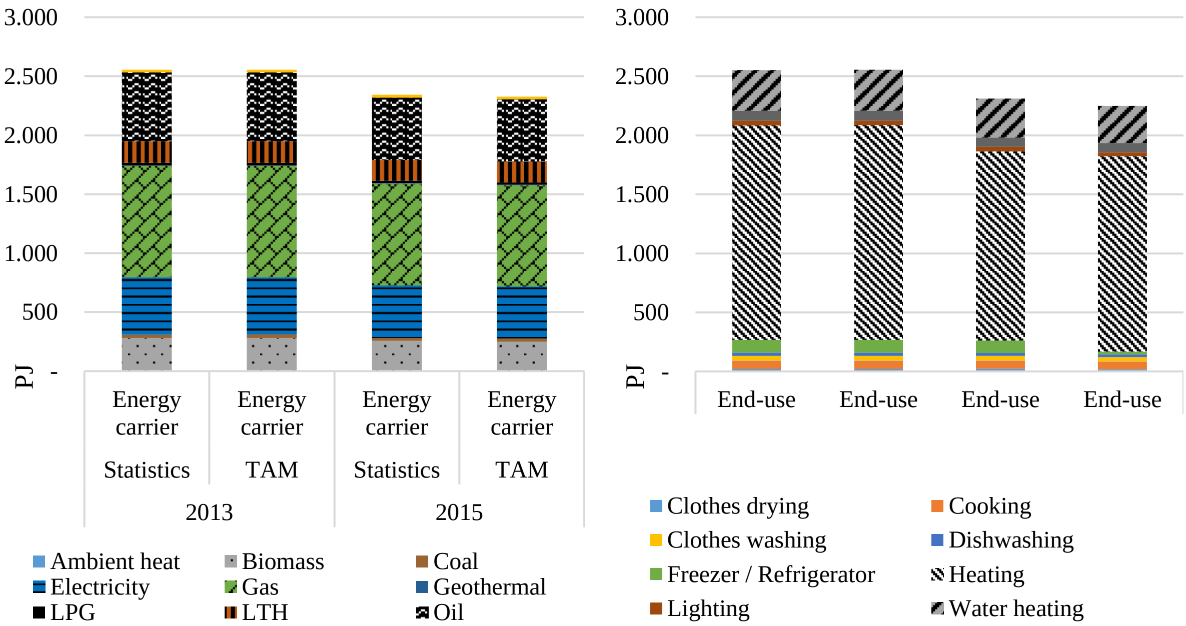


Figure 2.14: Comparison of input data and outputs from TAM-Households for the household sector for the base year 2013 and calibration for 2015 by energy carrier (left) and end-use (right)

Projections are based on expected overall energy carrier use for each sector given prognosis assumptions for 2020 and 2035 (BMU 2019b), such as population, households and average household size, as well as associate expected shifts of numbers of households between income groups and across building types, household income and expenditure, and available capital for investments (DESTATIS 2013; IMF 2019; DESTATIS 2019a; Eurostat 2020). As such the shift of the number of households in each income group and building type profile is given in Figure 2.15. There is an overall decline in the shares of lower income groups and reveal an increasing trend in 2060 of residence in multi-family homes (74%), 51.7% shares of home ownership and 9.3% living in rural areas.

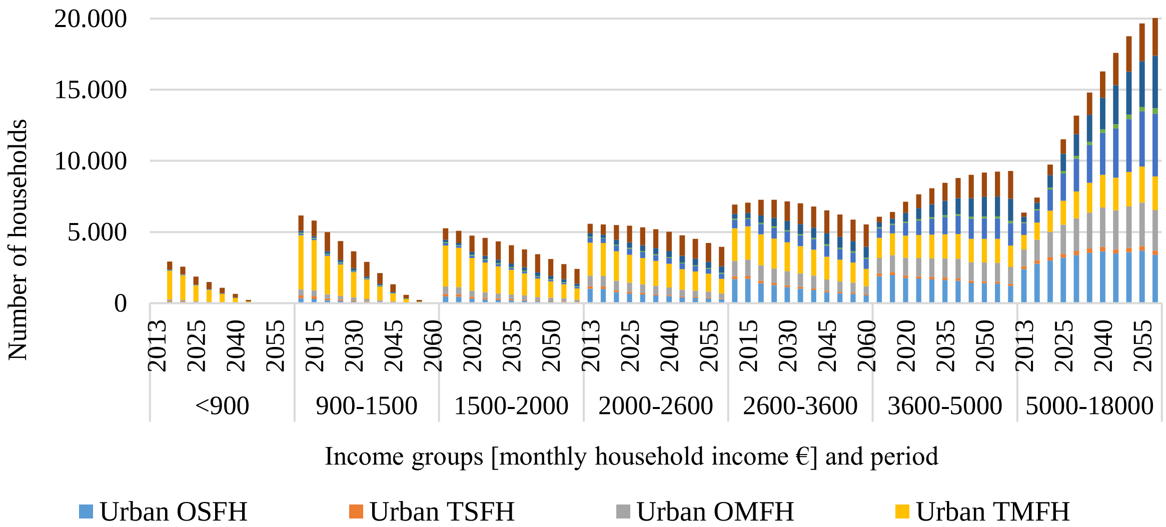


Figure 2.15: Projection of households by urbanisation and building type

2.4. Passenger transport

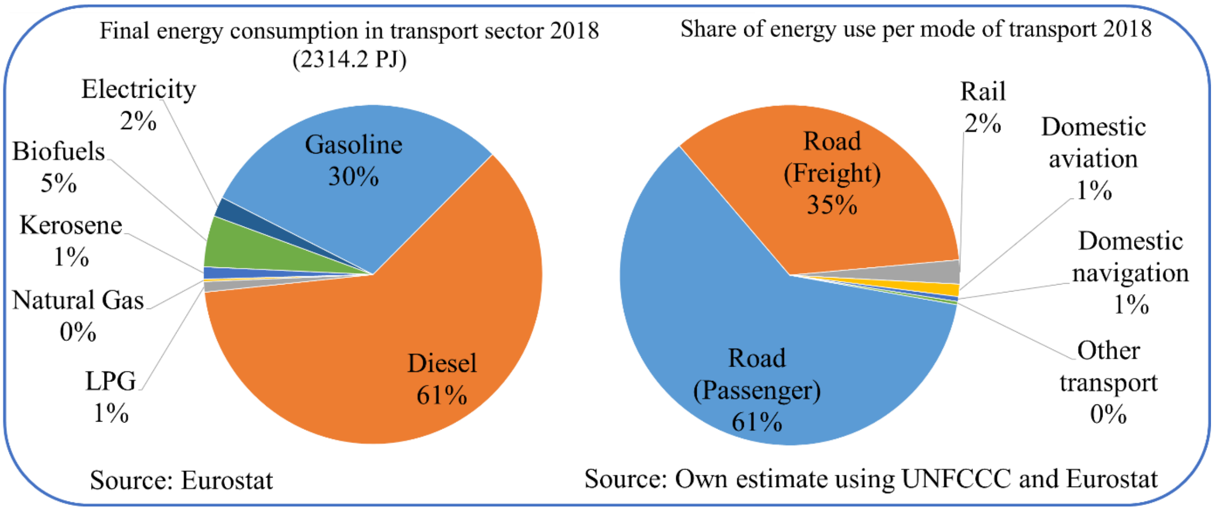


Figure 2.16: Overview of the fuel mix in the German transport sector

In 2018, the transport sector was responsible for 27.5% of the total final energy consumption (Figure 1.2). Around 61% of energy consumption in the German transport sector is in the form of diesel followed by gasoline (30%), biofuels (5%), electricity (2%), Kerosene (1%), LPG and natural gas (1%). The majority of fuel (61%) is consumed to transport the passenger while 35% of fuel is used to transport the freight using roads as shown in Figure 2.16. Therefore, the German transport sector is still heavily dependent on fossil fuels. In order to achieve the energy transition aspirations a major shift should take place. To achieve this major shift both technological (shift to low-carbon vehicles) and behavioural (modal shift) changes are required.

Within TAM, methodological improvements are implemented in the passenger transport sector (TAM-Transport) to enhance the behavioural realism of operation and investment decision of actor groups. In the typical structure of passenger transport sector in TIMES energy system models different technologies compete in consuming fuel commodities and less costs to fulfil an assigned end-use travel demands for each transport mode in Passenger kilometres (PKM). However, within TAM-Transport, beside the fuel commodities, the transport technologies consume money and time commodities. Therefore, the model allows competition to shift to alternative modes of transport for meeting travel demand e.g. using public transport instead of private car for heterogeneous groups of households. The public transport service provider actors are allowed to invest in new technologies and expand the infrastructure provided that the investment is less than their available capital. Moreover, both consumer and service provider actor groups could decide to invest in decentralised power generation technologies to produce electricity (self-generation) based on available budget.

In the first step, the transport demands are disaggregated by length (extra-short, short, medium and long) and location (urban and rural) assigned to the different income groups (i.e. consumer actors). In the second step, the Travel Money Budget (TMB) is introduced across different income groups representing the part of income that households assign to meet travel demand. In the third step, the Total Investment Budget (TIB) commodity is extended to take into account the investment decision of different income groups to uptake fossil fuel or low-carbon private transport technologies (i.e. fossil-fuelled or electric vehicle and traditional or electric bike) or invest in decentralised power generation (described in Households Section). In addition to costs, speed of transport modes is an important factor for making operation decision. In the fourth step, the Travel Time Budget (TTB) commodity is introduced, monetized and distinguished across income groups using the concept of Value of Time (VoT). Including these TMB and TTB commodities in the objective function allows the model to choose faster and cheaper available mode of transport to fulfil demand. In the fifth step, the infrastructure commodity is also introduced representing capacity bound that limits the amount of extra travel demand that can be accommodated by a certain mode. When the existing infrastructure is saturated, the providers of passenger transport must invest in new infrastructure, which involves a cost for the system. The details of these methodological extensions are provided by Ahanchian et al. (2019b) and presented in the following sections.

2.4.1. Disaggregation of actors

The identified actors who play significant role in passenger transport are divided to consumers and providers of passenger transport service.

Consumers of passenger transport

The behavioural patterns across different group of consumers are highly heterogeneous: households' energy demand can vary significantly from one household to another, which is explained by households' behaviour (Cayla and Maïzi 2015). Thus, the behaviour of travellers' towards modal choice is characterised by households' attributes. Within TAM-Transport travellers' heterogeneity is defined by categorising households in different groups. First by spatial characteristics: availability of modes, speed of modes and access to amenities changes across urbanisation types reflecting the existing infrastructure. Second by annual income: the income category of travellers is reflected in travel cost and travel time. As highlighted by several studies (Schafer and Victor 2000; Tattini et al. 2018a) wealthier people prefer to spend less time in transport modes so they choose the faster but more expensive modes of transport.

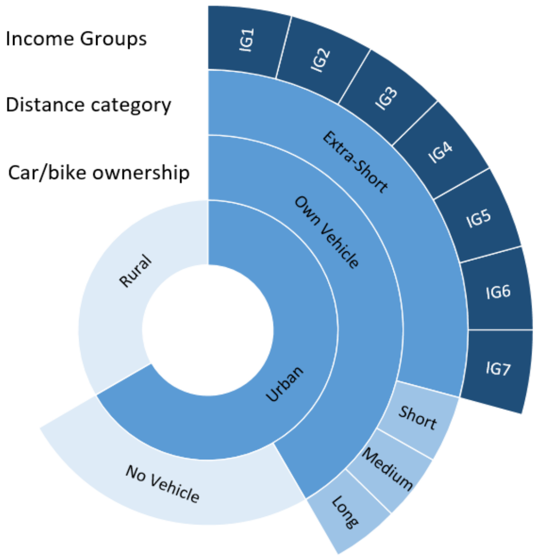


Figure 2.17: Consumer actors of passenger transport service

Figure 2.17 shows the consumer actors of passenger transport who are households grouped based on the annual income, level of mobility demand, vehicle/bike ownership and urbanisation type of the residential location. These actors face different options for operation and investment to fulfil mobility demand while participating in the energy transition. However, the investment decision of households is restricted by income and the budget they are willing and able to spend on the available options representing the heterogeneity of investment decision-making.

The total travel demand of households in passenger transport sector of Germany was 1,193.03 Billion passenger kilometres (BPKM) in 2013. Figure 2.18 shows the modal split of travel demand based on urbanisation type of residential location in 2013. Car is the most dominant mode both in urban and rural area. Public transport is composed of bus, U-Bahn, S-Bahn and D-Bahn (long distance trains). In 2013, around 72% of all trips were in urban area and 28% in rural area. Since the population is more concentrated in urban areas, the total travel demand of urban area is more than rural area. However, the overall travel demand in urban and rural area is around 14,700 and 17,660 km per person per year respectively. This means that people in rural area have more travel demand due to longer distance.

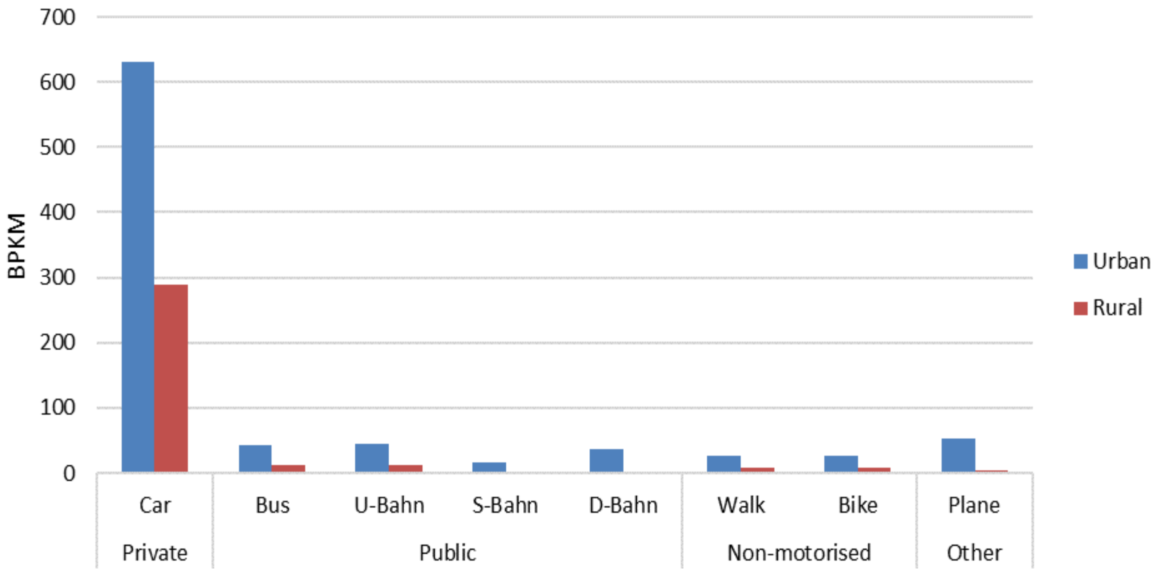


Figure 2.18: Split of travel demand based on urbanisation type in Germany 2013

In order to capture the mobility behaviour of citizens and the split of budget across income groups, the German mobility panel -Mobilitätspanel- (MOP)[3] data (Ecke et al. 2019) and the Income and Expenditure data by the German National Statistics Office (DESTATIS 2019b) are used respectively. Table 2.9 presents the categorisation of households based on annual household income in this study.

Table 2.9: Number of households across income groups in Germany 2013

	Total households ('000s), MOP	Household size (ppl/HH)	Number of car per 1000 person
IG1=<900	2,935	0.95	254
IG2=900-1500	6,170	1.29	465
IG3=1500-2000	5,273	1.49	601
IG4=2000-2600	5,578	1.80	514
IG5=2600-3600	6,925	2.37	635
IG6=3600-5000	6,078	2.69	542
IG7=5000+	6,368	3.04	460
Total	39,326	2.05	524

Figure 2.19 shows the modal split of travel demand split on income groups in Germany in 2013. The trend shows that the overall travel demand increases by income while it drops in the highest income group.

[3] MOP documents the national travel survey since 1994 designed and supervised by the Institute for Transport Studies of the Karlsruhe Institute of Technology (KIT).

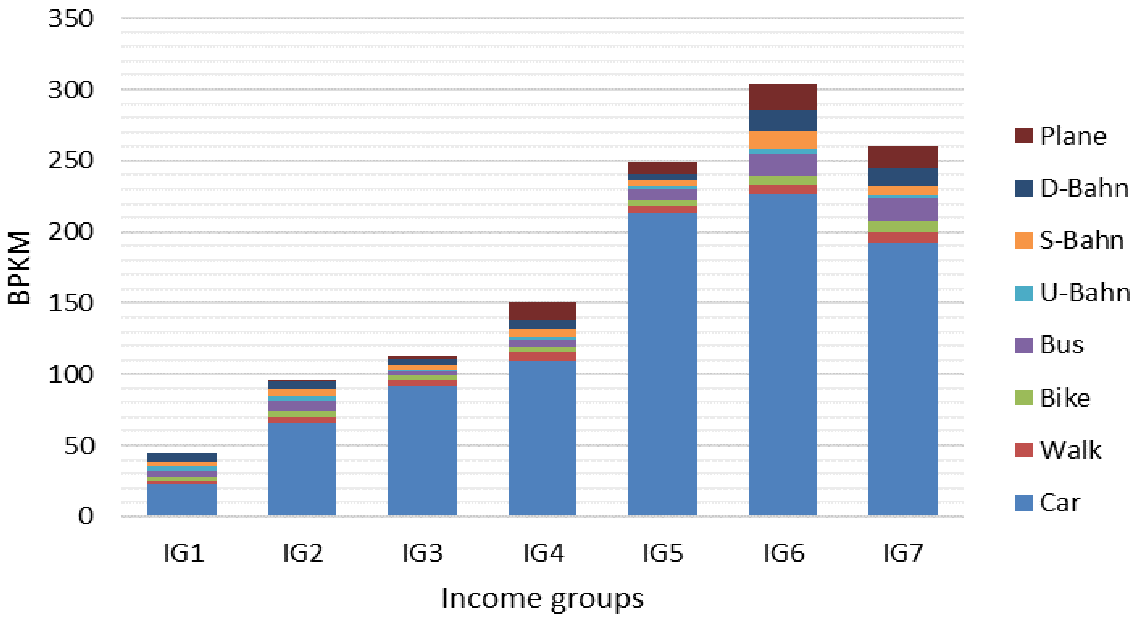


Figure 2.19: Split of travel demand based on income groups in Germany 2013

Table 2.10 shows the split of passenger travel demand based on trip length together with the amount of demand in BPKM. The classification of trip length is: Extra-short (XS) less than or equal to 5 km; Short (S) between 5 and 25 km; Medium (M) between 25 and 100 km; Long (L) more than 100 km. According to settlement patterns two regions are identified: urban (U) and rural (R) regions. The demand is disaggregated on the type of urbanisation area where the trip is originated and aggregated on all modes of transport.

Table 2.10: Travel demand split based on trip length and urbanisation type in 2013

	Abbreviation	Length	Urban Demand (BPKM)	Rural Demand (BPKM)	Total (BPKM)
Extra-Short	E	0<=5	103.45	28.66	132.11
Short	S	5<S<=25	291.69	99.70	391.39
Medium	M	25<M<=100	230.59	109.57	340.16
Long	L	100<L<=1000	237.91	91.45	329.36
	Total		863.64	329.38	

Table 2.11 shows the split of private cars based on engine capacity grouped according to fuel type. The Plug-in Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs) are defined based on two power ranges i.e. small and large. Other vehicle technologies such as CNG, LPG and Hydrogen Fuel Cell Vehicles (FCEVs) are also modelled. The operation and maintenance costs, investment costs and efficiency of private cars are taken from ADAC (ADAC 2019) and the market price in Germany. The available infrastructures such as roads, railways and bike lanes are taken from (Radke 2018).

Table 2.11: Split of private cars

	Abbreviation	Engine capacity (cc)	
		Gasoline	Diesel
Extra-Small	E	Less than 1000	Less than 1500
Small	S	1000 - 1600	1500 - 1800
Medium	M	1600 - 2000	1800 - 2400
Large	L	2000 – and more	2400 – and more

Providers of passenger transport

The provider actors of passenger transport are disaggregated based on the technologies (train, bus, airplane) and service type (long distance, regional, local) shown in Figure 2.20. These actors are facing several investment options such as expansion of public transport infrastructure to accommodate travel demand and renewable-based decentralised self-generation. Particularly, these actors can invest in plant scale PV sites and onshore and offshore wind farm considering the available potentials and different investment budget restrictions.

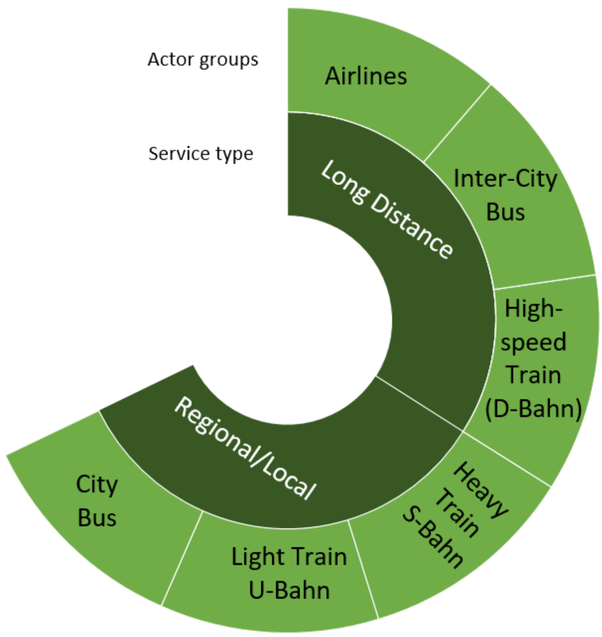


Figure 2.20: Provider actors of passenger transport service

2.4.2. Conceptual methodological improvements in TAM-Transport

Figure 2.21 shows an overview of the typical structure to represent passenger transport sector in TIMES energy system models. The end-use mobility demands for each mode are defined exogenously in passenger-kilometre (PKM) from the base year until the end of the modelling horizon. Therefore, there is no competition possible across the different transport modes to meet the demands. The technology database for the passenger transportation sector includes several fuels, a number of existing technologies and additional technologies that are available for future investments competing within a mode to meet several types of end-use demand. From an energy system perspective, different technologies compete in consuming commodities to fulfil the end-use travel demands. Some of the fuels make the transport sector integrated with the rest of the energy system (e.g. electricity, hydrogen and biofuels). This structure is technology rich with a fine representation of techno-economic dimensions of an energy system.

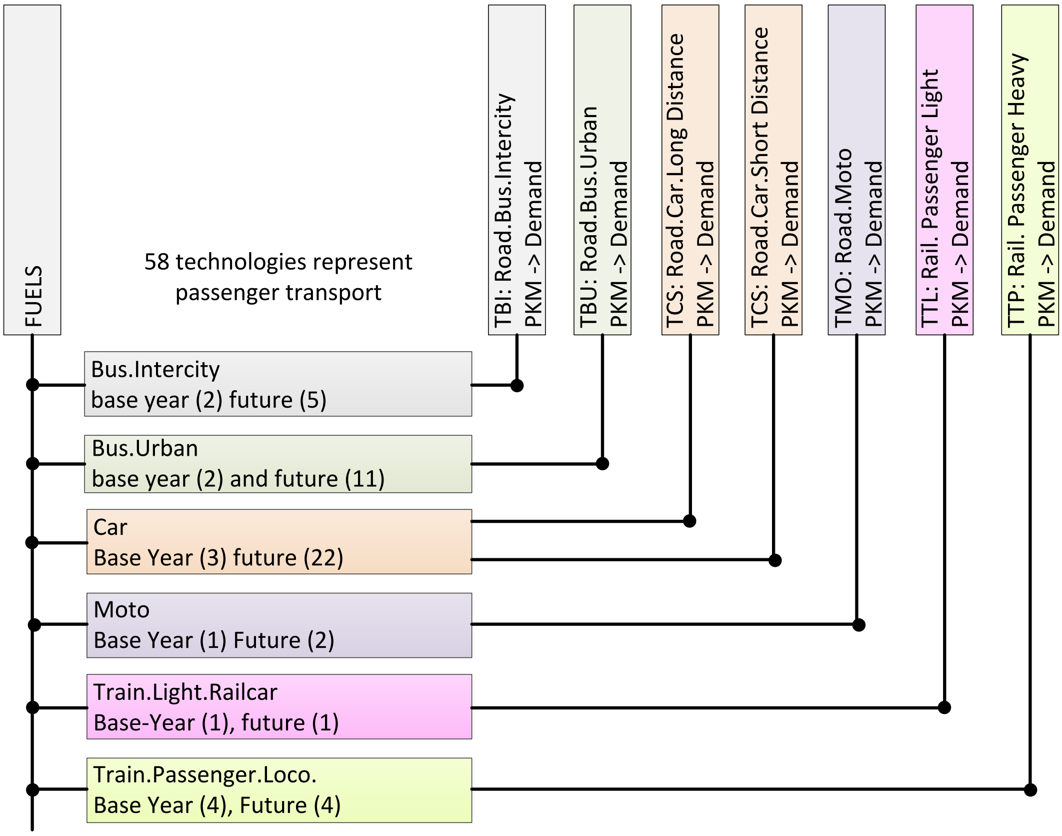


Figure 2.21: Typical structure of passenger transport in TIMES models

In order to improve behavioural realisms of consumer actors in passenger transport sector of Germany, the typical methodology was extended inspired from the tested approaches used in previous works (Daly et al. 2014; Pye and Daly 2015; Tattini et al. 2018a). Figure 2.22 provides a schematic representation of the structure of passenger transport sector in TAM-Transport.

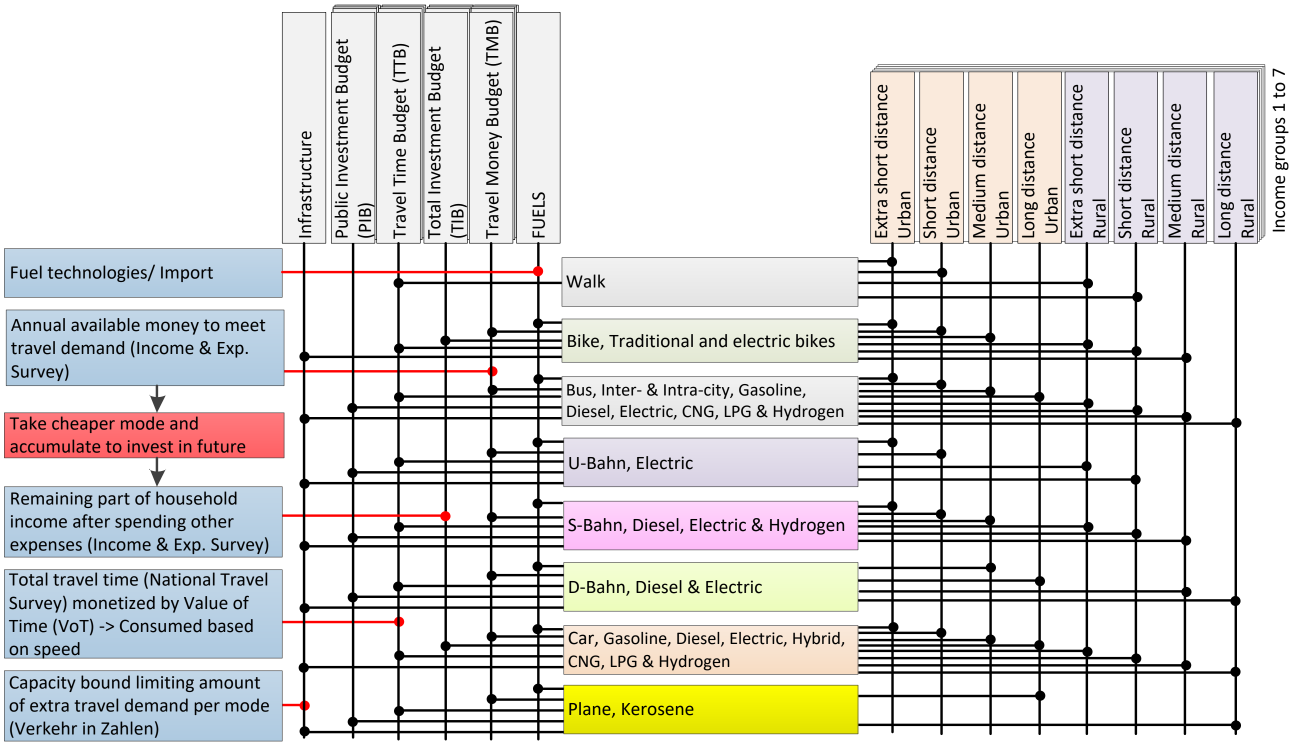


Figure 2.22: The structure of passenger transport sector in TAM-Transport

On the right hand side there are the exogenously disaggregated mobility demand commodities, which should be fulfilled by transport technologies (modes). The exogenous travel service demands expressed in billion passenger-km (BPKM) are defined as time series from the base year until the end of the modelling horizon. Instead of assigning a certain demand to each mode, the travel demand is disaggregated based on trip length and urbanisation type of residential location across income groups. These demand categories could be fulfilled by different modes depending on the model choice based on associated costs and time. The level of service and availability of infrastructure of each mode describes the capability to meet a certain demand type. For instance, walk can only fulfil extra short and short distance trips both in urban and rural area while, bike can also fulfil medium trips and so on. Moreover, the bike and car ownership are implemented in the model across different income group of TAM-Transport residential. This methodology extends the technology competition within the modes to competition across modes by aggregating the passenger modal travel demands into demand segments based on the distance range.

Within TAM-Transport, the transport modes do not consume just fuels, but also require money and time commodities in the input to fulfil the travel demand. Including money and time commodities in the objective function allows the model to choose faster and cheaper available mode of transport. Therefore, beside fuel commodities, several other commodities are introduced in the model. The Travel Money Budget (TMB) commodity represents the part of income that households assign to meet travel demand taken from income and expenditure survey for each income group. The tangible operation expenses of transport technologies (private and public) that consumer actors are facing, i.e. bikes and cars maintenance costs, fuel costs and public transport ticket price are formulated in a way to consume TMB commodity per each kilometre travelled using a certain technology.

The Total Investment Budget (TIB) is also a new commodity introduced in this model representing the remaining part of households' income after spending other household expenses (savings). In TAM-Transport, the TIB is considered as available budget that households could spend to invest in new private technologies, e.g. traditional and electric bikes and cars. Moreover, the actors who shift to cheaper mode of transport could accumulate this saving from TMB to TIB and spend it to invest in new technologies in future.

Travel Time Budget (TTB) is also a new commodity introduced in this model. The rationale for adoption of the TTB has been provided by (Schafer and Victor 2000), which claims that across different societies, historical periods, geographical areas and income classes people spend almost the same amount of time per day for traveling. Time is an important aspect of making decision to meet travel demand which has different values across income groups defined by Value of Time (VoT) to monetise the time. The concept of Value of Time (VoT) is a significant factor for calculating the intangible cost (Schafer and Victor 2000). The VoT is the marginal substitution cost between travel time and travel cost and it states how much a consumer is willing to pay to reduce the travel time of one unit (Mackie et al. 2003). For example, walking does not have tangible cost, but higher intangible costs due to travel time. The VoT is dependent on the purpose of the trip and the user's income level.

Incorporating TTB requires introducing the speed of transport technology (private and public) which is assumed constant in all technologies belonging to the same mode meeting certain demand with the exception of electric and traditional bikes. The total travel time budget for the German population in 2013 was 40.03 billion hours per year based on MOP. This corresponds to average of 81.4 minute per person per day meaning that the population in a certain income group is not willing to spend more time for their transport demand. Therefore, to meet a unit of a certain demand for a certain income group, each technology also consumes some TTB based on its type and the demand it supplies. In addition to a limit on the maximum available time, there is also a certain cost associated with each unit of TTB consumed by technologies to meet the demand for each income group. These (intangible) costs defined as VoT are also considered in the objective function to be minimised. For example, private cars are faster than the public transport in meeting the extra short to medium distance transport demands. Therefore, an income group with a higher value of time (richer income groups) might prefer to invest in a private car to meet their extra short to medium distance demand rather than using the public transport. However, this is the opposite for long distance demands, where the public but probably more expensive transport modes, such as airplane, are faster than private cars. Thus, there exists a trade-off for some income groups whether to buy a car for their shorter trips, or not because they will not use it for their longer trips. This trade-off is also included in this model, thanks to its total costs minimisation.

The investment decision of service provider actors is restricted by their available budget. Therefore, the public investment budget (PIB) commodity per service provider actor group is introduced to the model only available to public transport technologies. After all, investments in public transport technologies as efficient transport modes cannot be infinite. Therefore, when the PIB is exhausted, consumers will have to invest in private technologies or simply walk or bike. The infrastructures have capacity bound that limits the amount of extra travel demand that can be accommodated by a certain mode. When the existing infrastructure is saturated, the extra infrastructures required must then be provided by the new infrastructure technologies, which involve additional cost for the system.

2.4.3. Calibration and techno-economic assumptions

The Income and Expenditure data by the German National Statistics Office (DESTATIS 2019b) is used to capture the split of budget across income groups in the base year and projected based on the predicted GDP per capita growth in Germany over the modelling horizon and used to quantify TMB and TIB. The trend of investment budget for providers of public transport is representing public investment budget (PIB) restriction and is taken from (Radke 2018) developed proportional to the predicted GDP growth throughout the modelling horizon. The available infrastructures such as roads, railways and bike lanes together with the trend of investment budget for each actor group -projected based on the predicted GDP growth- are taken from “Verkehr in Zahlen” report (Radke 2018). Regarding time granularity, the transport sector is described at annual level, i.e. the model does not characterise intra-annual and intra-day variations. The spatial resolution of the model is on national scale. Other constraints derived from the National Travel Survey guarantee consistent travel habits and avoid unrealistic modal shifts.

The calibration process within TAM-Transport is accomplished by adjusting the parameters to reproduce the historical data in 2013. For instance, Table 2.12 compares the total number of vehicles in TAM-Transport and Verkehr in Zahlen (ViZ) in the base year.

Table 2.12: Comparing stock of technologies in 2013

Technology	Fuel Type	Unit	TAM-Transport	ViZ
Private Cars	Gasoline	Million Vehicle	30.810	30.810
	Diesel		12.031	12.031
	LPG		0.462	0.462
	CNG		0.076	0.076
	Hybrid		0.048	0.048
	Electric		0.005	0.005
	Total		**43.431**	**43.431**
Bus Long Distance	Diesel	Thousand Vehicle	12.416	12.871
	Gasoline		0.018	
Bus Short Distance	Diesel		16.539	16.562
	Gasoline		0.023	
	CNG		0.200	
	LPG		0.165	
	Electric		0.072	
	Total		**29.433**	**29.433**
Train Long Distance	Diesel	Thousand Seats	0.622	1.306
	Electric		0.684	
Train Short Distance	Diesel		0.559	0.941
	Electric		0.382	
	Total		**2.247**	**2.247**
Plane	-	Thousand	0.641*	1.282**

* Domestic airplanes
* Domestic and international airplanes

Figure 2.23 compares the split of modal shares resulted from TAM-Transport with the historical data reported in MOP in 2013.

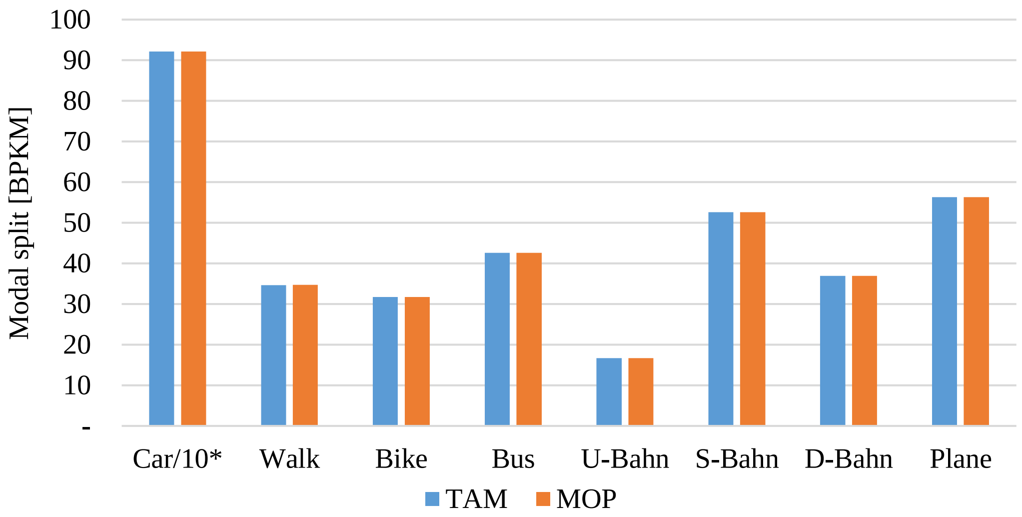


Figure 2.23: Comparing the modal split, TAM-Transport vs. historical data in Germany 2013[4]

[4] The car use amount is divided by 10, due to different order of magnitude compared to other modes.

The efficiencies of different technologies are adjusted to reproduce the historical fuel input reported by Eurostat and the amount of emissions reported by UNFCCC for Germany in base year. Figure 2.24 compares the fuel input to transport technologies to meet the passenger mobility demand resulted in TAM-Transport with the historical data reported in Eurostat in 2013.

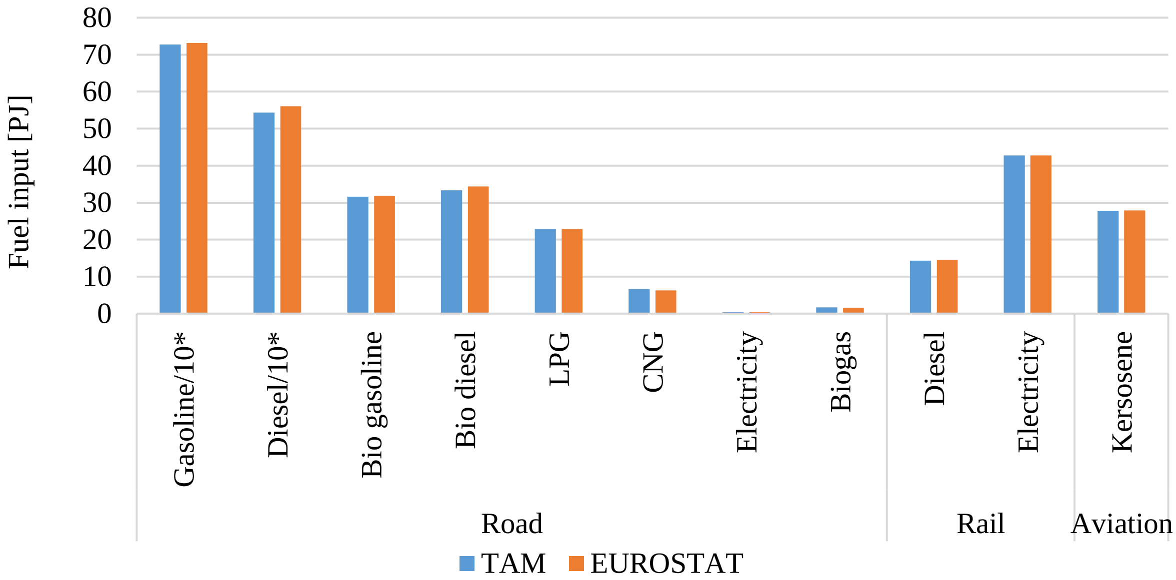


Figure 2.24: Comparing fuel input, TAM-Transport vs. Eurostat, Germany 2013[5]

Table 2.13 compares the respective environmental emissions resulted in TAM-Transport with the historical data reported in UNFCCC in 2013.

Table 2.13: Comparing environmental emissions TAM-Transport vs. UNFCCC 2013

		CO_2 [kt]		CH_4 [kt]		N_2O [kt]	
		TAM-Transport	UNFCCC	TAM-Transport	UNFCCC	TAM-Transport	UNFCCC
Private Cars	Gasoline	52,988.23	52,476.71	3.122	3.092	0.502	0.522
	Diesel	40,253.24	41,631.41	0.133	0.137	1.279	1.324
	LPG	1,457.94	1,471.83	0.044	0.045	0.031	0.032
	CNG	311.84	295.22	0.032	0.030	0.005	0.005
D-Bahn	Diesel	505.04	1,019.42	0.002	0.015	0.016	0.008
S-Bahn	Diesel	558.64		0.002		0.018	
Plane	Kerosene	2,036.88	2,153.63	0.069	0.073	0.068	0.072
Total		**98,111.82**	**99,048.22**	**3.404**	**3.392**	**1.919**	**1.962**
Buses	Gasoline	20.45	N/A	0.001	N/A	0.000	N/A
	Diesel	2,335.20	N/A	0.008	N/A	0.074	N/A
	LPG	37.82	N/A	0.001	N/A	0.001	N/A
	CNG	56.22	N/A	0.006	N/A	0.001	N/A

[5] The amount of gasoline and diesel use are divided by 10, due to different order of magnitude compared to other fuels.

2.5. Supply sector

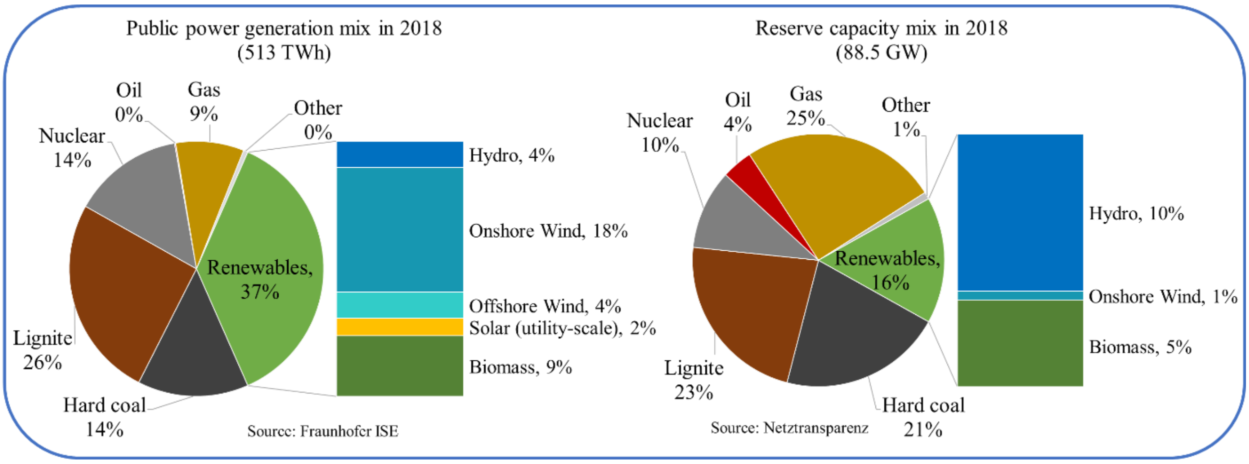


Figure 2.25: Some insight in the German energy supply sector

As shown in Figure 2.25 as of 2018 around 63% of the total electricity in the German public supply sector was generated in conventional power plants, including 14% nuclear and 50% fossil fuels (Fraunhofer ISE 2019). Nuclear energy and coal constituted almost 55% of the existing reserve capacity (Netztransparenz 2019), which are going to be phased out by the end of 2022 and 2038 respectively. Moreover, fossil fuels, specifically coal and gas, constitute about 73% of heat generation in the German district heating networks (AG Energiebilanzen e.V. 2019). Therefore, the German energy supply is still heavily dependent on conventional energies. In order to achieve the energy transition aspirations a major shift should take place.

However, the supply sector, just like the demand sectors, is not homogeneous. On one hand, there are various actors who invest in different technologies. These actors do not possess equal financial power and do not hold the same expectations about their investment and the associated rate of return. On the other hand, the renewable resources which should be utilised to decarbonise the supply sector are not evenly distributed across Germany. There is also a spatial mismatch between the renewable energy resources and demand zones. Thus, there is a need for long distance renewable electricity transmission within Germany. These two heterogeneity aspects are usually not represented in model-based energy system analysis.

In this study the typical structure of representing the supply sector in TIMES family of models is extended in order to better represent the reality of actors' rational investment decisions for public power and heat generation towards engagement in the German energy transition. The methodological improvements executed within TAM-E-Supply (the disaggregated supply sector model) include four major steps. In the first step, the investors in public power generation technologies are disaggregated to three main actor groups, namely utilities, institutional investors and citizens grouped in energy cooperatives taking into account their specific economic characteristics and preferences. The actors in the supply sector, obtain the required capital from various sources such as company creditors, equity holders, banks or even their own savings (in the case of citizens) resulting in different investment valuations and return expectations, which are reflected in their different cost of capital (i.e. investor specific discount rates or hurdle rates).

However, the actors benefiting from cheaper capital cannot invest unboundedly. Therefore, in the second step, the actors' specific budget restrictions as a restricting factor for investment decisions are introduced into the model based on historical data. Besides these different economic characteristics of the investing actors there is also some preferences with regard to certain renewable technologies which are implemented in the model based on the historical data on the ownership structure of installed renewable power generation capacities.

Since the environment, where the investors are located, affects actors' investment decision, the third step involves regional division of the German supply sector into four regions (north, east, south and west) providing an opportunity to study the impact of the spatial distribution of renewable potentials and demand as well as the inter-regional import and export of electricity. The fourth step includes grid aspects into the model. The existing inter-regional transmission grid capacities, the distribution grid losses, the operation costs of existing grids and the investment costs of expanding the grid for power transmission between the regions are considered. The methodological extensions in TAM-E-Supply improve the representation of actors' diversity and their environment in order to more realistically capture the heterogeneity of investment decisions. The details of these improvements are described by Tash et al. (2019).

It is to be noted that the rest of the supply sector including fuel mining, processing, import and transportation as well as biomass, biogas and hydrogen production technologies in different regions and also refineries are considered in the model too. However, the model expansions with the exception of the region divisions do not include this part of the supply sector.

2.5.1. Disaggregation of actors

Investors, as actors in the supply sector, have different expectations for their investments because of the different ways they obtain the required capital for an investment in an energy project. For instance, a company's creditors or equity holders do not finance it for free. They demand to be paid for delaying their own consumption and assuming investment risk (Majaski 2019) and also to compensate for other investment opportunities they refuse to take. Thus, the company should return some profits on top of the money they borrow which is called the "cost of capital". The cost of capital is different from investor to investor. It applies to individual investors too because they borrow from a bank or when they have the capital from their own savings they always have the opportunity to invest their money in other projects or simply put it in a bank. Therefore, it only makes sense for an investor to proceed with a new project if its expected revenues are larger than its expected costs, in other words, it needs to be profitable and the return should be at least equal to the cost of capital, which is called the Minimum Acceptable Rate of Return (MARR).

The investors with lower cost of capital tend to invest in capital intensive technologies which have low or almost no future operational costs (CAPEX), such as most of the renewables like offshore wind. By contrast, the investors with high cost of capital opt for less capital intensive technologies, which typically have high future operational costs (OPEX), especially due to fuel costs, such as most of conventional and fossil technologies (Wüstenhagen and Menichetti 2012). This statement might seem obvious. Nonetheless, the former actors do not have access to unlimited inexpensive capital and cannot invest unboundedly, otherwise the transition to a decarbonised energy system would be much cheaper. Therefore, it is quite advantageous to know where this "limited low cost of capital opportunity" should be deployed and also with regard to which expensive decarbonising technology so that the system could economically benefit the most from it and the energy transition could take place more quickly at lower costs.

In order to represent actors' diversity within TAM-E-Supply , the actors are disaggregated to utilities, institutional investors and citizens including individuals and energy cooperatives. These actors are further characterised by their different cost of capital and their budget restrictions for investments in new decarbonising technologies in different regions. This disaggregation is adopted based on the extensive investigations of current power generation ownership structure in Germany by Holstenkamp (2013) and then followed by trend:research GmbH (2017). The cost of capital for each of these actor categories are taken from Helms et al. (2015), which also uses the same disaggregation from the above mentioned references. Figure 2.26 shows the ownership distribution of installed renewable capacities for power generation in Germany in 2016.

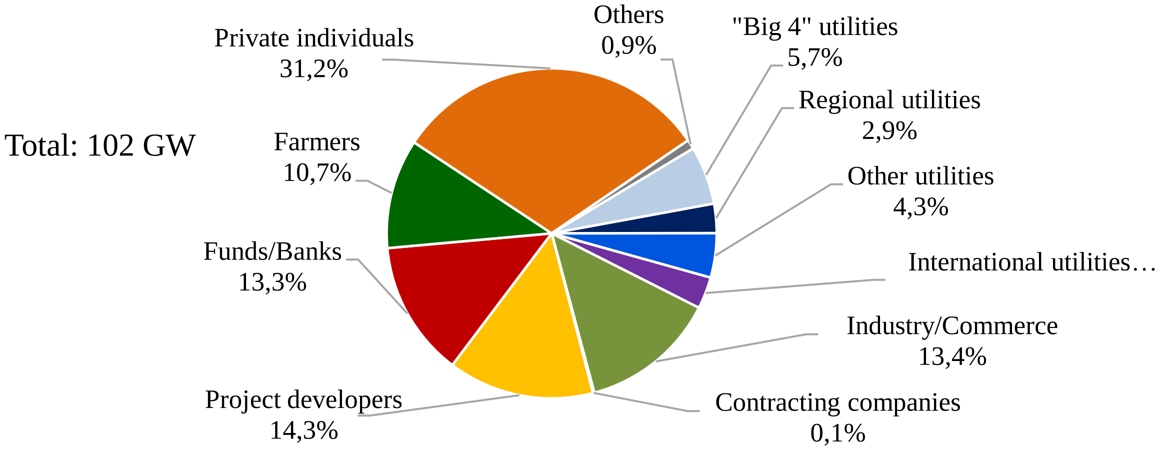


Figure 2.26: Ownership distribution of installed renewable capacities, Germany 2016[6]

Helms et al. (2015) have categorised all utilities into the “Utilities” category, industry, contracting companies, project firms and funds/banks into the “Institutional investors” category and finally private individuals and farmers into the “citizens” category and has offered a cost of capital estimation for each category. For the sake of avoiding unnecessary complexity we follow the same classification. Table 2.14 shows the summary of this classification. It is to be noted that not all of the owned capacity from an actor generates for the public supply sector. Especially there are some capacities (PV and biomass) owned by Industry/Commerce, Farmers and private individuals which generate for sector self-consumption. These are excluded in the following table and not considered in the calculations for the supply sector.

Table 2.14: Assignment of actors into actor groups, 2016

Actor	Actor ownership including self-consumption [MW$_{el}$]	Actor ownership excluding self-consumption (only for the public supply sector) [MW$_{el}$]	Actor group	Actor groups share in public renewable capacities
"Big 4" utilities	5844	5844	Utilities	23.24%
Regional utilities	2935	2935		
Other utilities	4437	4437		
International utilities	3193	3193		
Industry/Commerce	13675	3043	Institutional investors	44.43%
Contracting companies	137	137		
Project developers	14622	14622		
Funds/Banks	13574	13574		
Farmers	10966	4438	Citizens	32.33%
Private individuals	31842	18392		
Others	936	936	Rest (neglected)	

[6] The capacities of the industry, households and the rest of the demand sector which serve as self-consumption and belong to sections 2.2, 2.3 and 0 respectively are included in this figure. The exclusion of these capacities is explained below.
Source: trend:research GmbH 2017.

The total ownership shares of all utilities in the public installed renewable capacity in 2016 was less than 24%, while the institutional investors and citizens owned around 44% and 32% of the capacities respectively. Unlike the conventional technologies, where the utilities are dominant, most of the renewable technologies are owned by the new-comer actors. This reveals the significant role that the unconventional investors play in the development of the renewable electricity generation, which is addressed in this project.

Figure 2.27 shows the development of ownership structure of total public renewable installed capacities (excluding capacities located in demand sectors) from 2004 to 2018. The original data set also contained the ownership structure of each individual renewable technology separately. These technologies are photovoltaic, offshore wind, onshore wind, biomass, biogas, hydro and geothermal energy. The figures for 2017 and 2018 were estimated by extrapolation of the development data from 2010 to 2016. Since this data set contains information about the actual installed capacity by the end of each year, some simple calculations using the average lifetime of each technology were done to calculate the amount of yearly installations of new capacities for the public sector by each actor from 2005 to 2018.

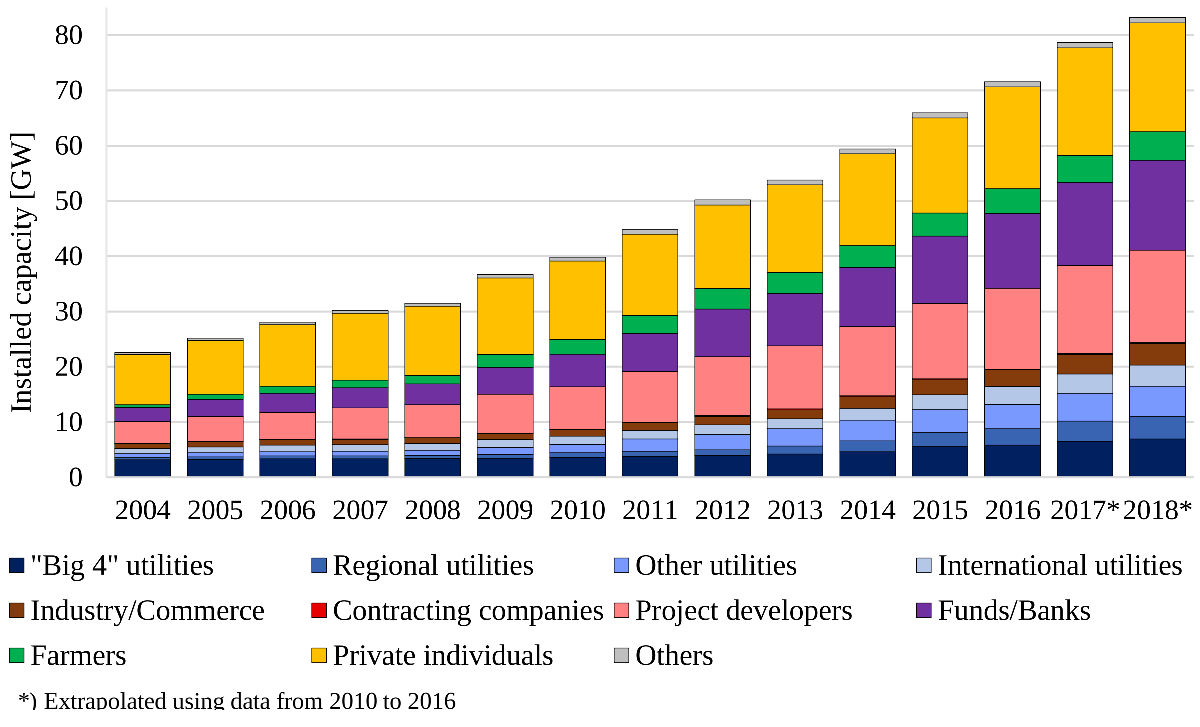


Figure 2.27: Ownership structure of renewable installed capacities from 2004 to 2016[7]

Subsequently the amount of investments (in million Euros) by each actor group for the public sector mentioned in Table 2.14 was calculated using the historical data on the specific investment costs of each technology. The overall results were then compared to the data

[7] Source: trend:research GmbH 2017 and own calculations

published by AGEE-Stat (2019) indicated in Table 2.15 and minor corrections were made in the calculations so that the total investments by all actors represent the data from AGEE-Stat.

Table 2.15: Yearly investments in renewable power plants for the supply sector 2005-2018[8]

in million €	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Hydro	230	210	270	300	410	310	260	180	130	90	80	60	30	20
Onshore wind	2490	3220	2470	2540	2800	2110	2860	3550	4490	7060	5370	6910	7280	3280
Offshore wind	0	0	30	170	470	450	610	2440	4270	3940	3680	3380	3420	4210
Photovoltaic	854	721	1367	1625	3209	3489	4111	4041	1272	557	381	589	596	812
Solar thermal	630	990	760	1700	1490	990	1060	950	860	790	800	700	540	470
Geothermal, Ambient heat	410	940	920	1230	1140	960	990	1060	1090	1080	1020	1210	1310	1370
Biomass (power)	1736	2200	1998	1740	2002	2262	2966	779	404	48	200	169	258	354
Biomass (heat)	1510	2300	1500	1760	1610	1210	1320	1500	1530	1360	1270	1230	1200	1210
Total	**7860**	**10581**	**9315**	**11065**	**13131**	**11781**	**14177**	**14500**	**14046**	**14925**	**12801**	**14248**	**14634**	**11726**

2.5.2. Conceptual methodological improvements in TAM-E-Supply

By excluding the investments, which were made for self-generation within the demand sectors from the total figures (Industry, households and the rest), the investments which were made solely for the energy supply sector were calculated. Among the latter numbers, the years with the maximum investments by each actor group were chosen as the years which reflect the actual capacity of that actor groups for investments in decarbonising technologies. These are 11.081 and 4.254 billion Euros for institutional investors and citizens[9] respectively. The investments by utilities is assumed to be unbounded since they have the highest cost of capital.

In addition to that, a limited number of technology types can be at the disposal of each actor group, reflecting the existing reality that technologies are differently "preferred by" or "accessible to" actor groups. For example, it is assumed in this project that citizens and institutional investors mainly invest in decentral electricity technologies generating low and medium voltage electricity in the distribution network with the exception of institutional investors investing in onshore and offshore wind parks (high voltage central technologies) as shown in Figure 2.28. Both institutional investors and citizens are allowed to invest in decarbonising district heating technologies.

[8] Excluding the investments for self-generation in demand sectors (industry, households and the rest) Source: AGEE-Stat 2019.
[9] Energy cooperative (Private household investing in rooftop PV are therefore excluded.)

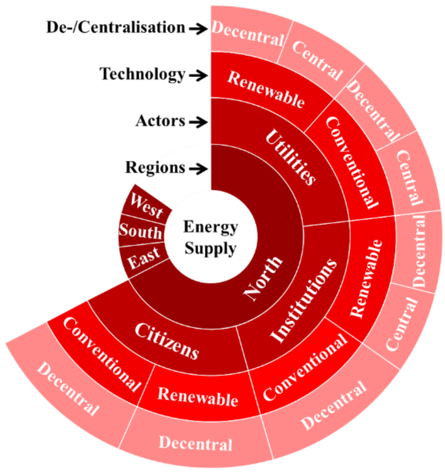


Figure 2.28: Access of actors to generation technologies in the supply sector

This section demonstrates the implementation of the actors disaggregation, regional division, grid aspects and matching of supply sector to other sectors. All model improvements in TAM-E-Supply are shown in Figure 2.29 and explained in the following sub-sections.

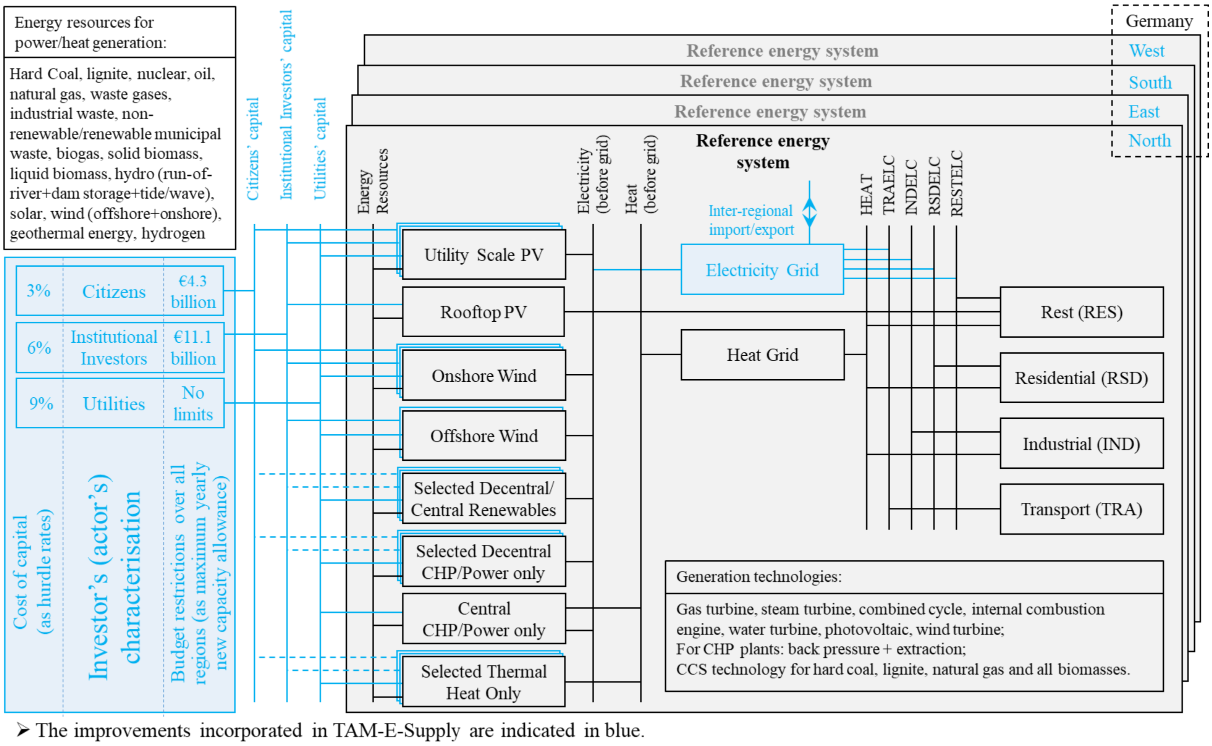


Figure 2.29: The structure of TAM-E-Supply

Implementation of the actors disaggregation

- *Cost of capital*

The discount rate is a tool which makes it possible to estimate how much the project's future cash flows would be worth in the present. One method for investment valuation is to discount all the future cash flows of an investment project back to the reference year using the investors cost of capital or MARR that an investor expects from investing into a certain project (Steinbach and Staniaszek 2015). If the discounted amount is at least equal or greater than the initial investment, the investor decides to invest in that project. This investor's specific discount rate, also called hurdle rate (the actor's minimum acceptable discount rate for investment valuation), is equal to the ultimate cost of capital of an investor considering the risks and opportunity costs[10]. Therefore, if we include these different costs of capital as different actors' specific discount rates (hurdle rates) in the objective function formulation of the model to discount future cash flows, including costs and reimbursements, back to the user-defined reference year, we can actually include different investment valuations of the actors in calculating the system costs and hence in the model technology choices in different regions.

As discussed in section 2.1, TIMES model provides the opportunity to set different cost of capital (hurdle rates) for different investors by setting the actor's hurdle rate on the technologies at its disposal for investment. The actor's cost of capital replaces the global discount rate for those technologies in the TIMES objective function (shown in Equation 2.4).

In TAM-E-Supply there are three different actor groups, namely utilities, institutional investors and citizens. Thus, the objective function of TAM-E-Supply changes to Equation 2.6.

$$\begin{aligned} &Total\ discounted\ system\ costs = \\ &\sum_{r=1}^{R}\sum_{y\in YEARS}\Bigg(\sum_{t_A\in TECHS_A}\left(1+d_{r,y,t_A}\right)^{REFYR-y}\times ANNCOST(r,y,t_A) \\ &\qquad+\sum_{t_B\in TECHS_B}\left(1+d_{r,y,t_B}\right)^{REFYR-y}\times ANNCOST(r,y,t_B) \\ &\qquad+\sum_{t_C\in TECHS_C}\left(1+d_{r,y,t_C}\right)^{REFYR-y}\times ANNCOST(r,y,t_C) \\ &\qquad+\sum_{t_R\in TECHS_R}\left(1+d_{r,y,t_R}\right)^{REFYR-y}\times ANNCOST(r,y,t_R)\Bigg) \end{aligned}$$

Equation 2.6

Where:

$TECHS_A$	is the set of all technologies available to actor A (e.g., citizens);
$TECHS_B$	is the set of all technologies available to actor B (e.g., Institutional investors);
$TECHS_C$	is the set of all technologies available for actor C (e.g., utilities);
$TECHS_R$	is the rest of technologies not belonging to any of above actors (the rest);
d_{r,y,t_A}	is the specific discount rate for actor A representing its cost of capital;
d_{r,y,t_B}	is the specific discount rate for actor B representing its cost of capital;
d_{r,y,t_C}	is the specific discount rate for actor C representing its cost of capital;
d_{r,y,t_R}	is the specific discount rate for the rest R representing global discount rate;
$ANNCOST(r,y,t_A)$	is the total annual costs of technologies of actor A in region r and year y;
$ANNCOST(r,y,t_B)$	is the total annual costs of technologies of actor B in region r and year y;
$ANNCOST(r,y,t_C)$	is the total annual costs of technologies of actor C in region r and year y;
$ANNCOST(r,y,t_R)$	is the total annual costs of technologies of "the rest" in region r and year y;

[10] Please refer to Steinbach and Staniaszek (2015) and Helms et al. (2015) for further details on investment valuation in energy generation projects.

The investments in photovoltaic rooftop potential in the industrial and residential as well as the rest of the demand are considered in their respective models since they serve as self-generation for those sectors. However, the rooftop potential in the "Rest" is represented in the supply sector and only institutional investors have access to it.

Nevertheless, there are also some renewable technologies available to several actor groups such as utility scale PV, onshore and offshore wind. For instance, three different versions of the onshore wind technology with the same technical specifications exist in the model, each with a different investor's specific discount rate representing the respective actor's cost of capital. The levels of the different hurdle rates for the three actor groups in TAM-E-Supply are depicted in Figure 2.29.

There are also some technologies which do not generate electricity or heat and hence do not belong to any of the existing actors, such as biomass processing technologies or the grid. These technologies belong to the category of "the rest" within the technologies and receive the original global discount rate. Equation 2.6 shows the improved mathematical formulation of the objective function to be minimised, considering actors disaggregation.

- *Budget restriction*

As discussed in section 2.1, budget restriction is also a key driving factor which limits investments in capital-expensive renewable technologies by the actors with access to less expensive capital. Therefore, in order to emulate this effect in a more realistic way, the budget restriction of the actors with a lower cost of capital should be reflected in the model. The budget restrictions explained in the beginning of section 0 are implemented using a user constraint on each actor group over the four existing regions in TAM-E-Supply , reflecting the fact that actors can freely invest in regions other than their own as well, which is already the case in the German supply sector. Equation 2.7 and Equation 2.8 show the mathematical formulation of the respective constraints in the optimisation problem representing the budget restrictions. Figure 2.29 depicts the maximum available budgets.

$$\sum_{r=1}^{R} \sum_{y \in YEARS} \sum_{t \in TECHS_A} new\_cap_{r,y,t_A} \times inv\_cost_{r,y,t_A} \leq Budget_A \qquad \text{Equation 2.7}$$

$$\sum_{r=1}^{R} \sum_{y \in YEARS} \sum_{t \in TECHS_B} new\_cap_{r,y,t_B} \times inv\_cost_{r,y,t_B} \leq Budget_B \qquad \text{Equation 2.8}$$

Where:

new_cap_{r,y,t_A}	is new capacity of a technology of actor A built in year y in region r;
inv_cost_{r,y,t_A}	is the specific investment cost of the above (equal across regions/actors);
$Budget_A$	is the maximum yearly budget available to actor A (e.g. citizens);

new_cap_{r,y,t_B} is new capacity of a technology of actor B built in year y in region r;
inv_cost_{r,y,t_B} is the specific investment cost of the above (equal across regions/actors);
$Budget_B$ is the maximum yearly budget available to actor B (e.g. institutional investors);

It is assumed that the utilities with highest cost of capital do not have any budget restrictions and can act in a complementary manner to make the balance between the actors.

Regional division and grid aspects

The rationale for incorporating a regional division in TAM-E-Supply is due to the variable geographical distribution of renewable resources and electricity demand as well as inter-regional electricity exchanges. On the one hand, the levelised costs of electricity generation from renewables, especially wind and solar, are different due to meteorological differences (also shown by McKenna et al. (2014), Wirth (2018), Kost et al. (2018), Bofinger et al. (2011), Schmidt and Mühlenhoff (2009), Diekmann et al. (2008)), which provides different cash flows for actors with the same economic characteristics but located in different regions, leading to dissimilar investment decisions. Thus, the decision to invest in a particular technology is crucially dependent on the region as well. On the other hand, the available renewable potential in a region might not match the level of demand in that region. Therefore, this regional imbalance in the demand and renewable supply should also be addressed by imports and exports or investments in non-renewable technologies, perhaps equipped with carbon capture and storage to comply with environmental targets. Furthermore, the current generation mix is different in Germany. For instance, nuclear power plants are located in the west and north and their phasing out impacts these regions the most. On the other hand, there is more generation from lignite in the east due to its historically different economic development (LAK-Energiebilanzen 2019).

This results in the possibility that the same actor might decide differently if situated in a different environment. In TAM-E-Supply , Germany is divided into four regions each of which consisting of several entire federal states. Although it is possible to have a higher spatial resolution representing all states separately, these four regions (namely north, east, south and west[11]) are assumed to be enough for demonstrating how regional differences can affect the energy supply sector.

Another aspect affecting diverse actors' optimal investment decisions is grid connection. In a particular condition, where further renewable generation is more expensive in one region

[11] North: Bremen, Hamburg, Lower Saxony, Mecklenburg-Vorpommern, Schleswig-Holstein; East: Berlin, Brandenburg, Saxony, Saxony-Anhalt, Thuringia; South: Baden-Württemberg, Bavaria; West: Hesse, North Rhine-Westphalia, Rhineland-Palatinate, Saarland

than in its neighbouring regions, two alternatives exist: 1) investment in transmission grid expansion to import cheaper renewable electricity or 2) investment in more expensive renewables inside the region (discussed further by Fürsch et al. (2013)). The optimal possibility among all alternatives can only be discovered when the grid extension costs and grid losses are considered. Within TAM-E-Supply , the existing inter-regional transmission grid capacities, its losses and the costs of new investments in power transmission between the regions are considered. Distribution grid losses and operational costs are also approximated. The costs of necessary transmission grid extensions due to future capacity expansion of wind and utility-scale solar capacities as well as the costs of necessary distribution grid extensions due to future expansion of rooftop solar capacities are considered as well. The techno-economic data for both transmission and distribution grid modelling are taken from (Simoes et al. 2013a).

Considering all the evidence, it appears that optimal actor investment performance varies in different environments and, yet again, a similar question arises as to where which specific actor should be incentivised to invest in which technology so that targets are met at lower costs? It can only be answered if the model includes regional differences in renewable energy sources and demand, and considers grid aspects to a sufficient extent.

Matching the supply sector to other sectors

Since the supply sector constitutes of four regions while the other sectors consider only one region there should be a mechanism, which manages the difference in the number of regions of the sectors especially for the sake of model coupling. The total demand in each sector and in each milestone year is distributed across regions in the supply sector using the prognosis of regional GDP, regional population or regional GDP per capita. For example, the industry electricity and heat demands in each milestone year are taken from the industry sector model, however, in one national region. Then the GDP development of each region in the supply sector is extrapolated using the historical data on GDP development of federal states from "Volkswirtschaftliche Gesamtrechnungen der Länder" (Statistische Ämter der Länder 2019). Using the same proportions of the regions in total GDP, the industry demand for each region in each milestone year is calculated. In order to distribute the residential demand to the regions in the supply sector, a similar approach is used. However, instead of using the regional GDP development, the regional population development is used based on the data from "Bevölkerungsentwicklung in den Bundesländern bis 2060" (Statistisches Bundesamt 2015). For the transport sector as well as the rest, the development of regional GDP per capita is used to distribute their demands to regions.

2.5.3. Calibration and techno-economic assumptions

The supply sector model is also calibrated to 2013 and 2015 with respect to public electricity and heat generation of different technologies in the four regions. Both the capacities and generation are calibrated according to the historical data. The fuel consumption is calibrated as well. The data on public generation capacities are taken from the power plant list published periodically by Bundesnetzagentur (Table 2.16) (BNetzA 2019). They are then cross checked with the data from DESTATIS (DESTATIS 2019c).

The data on generation and fuel consumption are taken from states energy balances published by states statistics offices available at LAK-Energiebilanzen (2019). In some cases where the states' energy balances lacked necessary data other sources are used such as the German biomass research centre (DBFZ) for data on biomass technologies (Scheftelowitz et al. 2015) or AFGW on CHP and heat generation technologies (AGFW 2016). At the end the final calibration is cross-checked with the overall detailed German energy balance.

Table 2.16: Regional public net electricity generation capacities including CHPs in 2013[12]

State	Model region	Hard coal	Lignite	Nuclear	Oil	Gas	Waste	Biomass	Geo-thermal	Hydro	Offshore wind	Onshore wind	Photo-voltaic	Dam	Pump storage	Total
		MW$_{el}$														
Baden-Württemberg	South	4215	0	2712	700	1126	135	754	1	756	0	595	4934	0	1873	17801
Bayern	South	843	0	5257	988	4416	213	1089	22	1812	0	907	10447	118	550	26661
Berlin	East	777	164	0	327	1106	36	27	0	0	0	2	72	0	0	2512
Brandenburg	East	0	4409	0	334	846	152	401	0	5	0	5202	2811	0	0	14160
Bremen	North	874	0	0	88	170	91	4	0	10	0	126	36	0	0	1398
Hamburg	North	194	0	0	38	143	24	42	0	0	0	56	35	0	0	532
Hessen	West	753	34	0	25	1610	127	216	0	63	0	822	1670	20	623	5962
Mecklenburg-Vorpommern	North	508	0	0	0	287	30	311	0	3	48	2123	1294	0	0	4604
Niedersachsen	North	2190	352	2689	59	4195	106	1181	0	51	460	7465	3409	0	220	22377
Nordrhein-Westfalen	West	13012	10764	0	504	8352	563	644	0	159	0	3302	4033	15	291	41639
Rheinland-Pfalz	West	13	0	0	0	1857	102	145	0	250	0	2186	1761	0	0	6313
Saarland	West	2156	0	0	0	164	27	12	0	11	0	196	378	0	0	2943
Sachsen	East	0	4325	0	17	582	27	249	0	95	0	1050	1503	0	1085	8932
Sachsen-Anhalt	East	0	1152	0	227	779	201	390	0	25	0	3969	1684	0	80	8506
Schleswig-Holstein	North	730	0	1410	537	20	30	325	0	4	0	3647	1433	0	119	8255
Thüringen	East	0	0	0	0	478	17	229	0	32	0	1069	1054	0	1509	4388
Total	North	4496	352	4099	722	4815	281	1863	0	68	508	13416	6207	0	339	4496
Total	East	777	10050	0	905	3791	433	1295	0	156	0	11292	7124	0	2674	777
Total	South	5058	0	7969	1688	5542	348	1844	23	2568	0	1502	15381	118	2423	5058
Total	West	15934	10798	0	529	11982	819	1016	0	482	0	6506	7843	35	914	15934
Total	DE	26265	21200	12068	3843	26130	1881	6018	23	3274	508	32717	36555	153	6350	176984

Table 2.17 indicates the gross electricity generation in states (model regions) by source in 2013. This data is used for the calibration of power generation in 2013.

[12] Source: BNetzA 2019.

Table 2.17: Public net electricity generation in states (regions) by source in 2013[13]

State	Model region	Coal	Lignite	Nuclear	Oil	Gas	Other non-renewable	Biomass	Hydro	Wind	Solar	Other renewable	Total
		GWh											
Baden-Württemberg	South	18386	0	19053	267	3462	2319	3930	5537	667	4028	163	57812
Bayern	South	4361	0	40663	1259	8694	942	7269	12959	1348	9043	265	86801
Berlin	East	3644	631	0	49	3062	56	208	0	5	48	0	7703
Brandenburg	East	0	32716	0	78	2967	2269	3042	20	7494	2272	142	51000
Bremen	North	4826	0	0	29	283	1181	391	41	261	23	7	7043
Hamburg	North	1115	0	0	21	675	106	199	1	75	25	51	2268
Hessen	West	4107	53	0	21	4212	894	1572	387	1226	1394	105	13970
Mecklenburg-Vorpommern	North	2901	0	0	106	1032	0	2074	8	3688	853	39	10701
Niedersachsen	North	12041	1449	21319	79	5654	2157	7770	286	12918	2579	119	66371
Nordrhein-Westfalen	West	47740	76908	0	1395	16563	9821	5563	460	4929	3121	580	167080
Rheinland-Pfalz	West	79	0	0	576	10514	746	953	1238	3042	1418	82	18648
Saarland	West	9014	31	0	49	249	719	173	121	282	281	3	10922
Sachsen	East	5	30974	0	66	3389	899	1488	311	1559	1180	69	39940
Sachsen-Anhalt	East	0	6819	0	27	3658	1257	2656	96	5992	1311	64	21878
Schleswig-Holstein	North	3339	0	11093	145	721	342	2558	6	6682	1248	57	26192
Thüringen	East	0	0	0	0	1835	1517	1711	269	1496	752	27	7608
Total	North	24223	1449	32412	380	8365	3786	12992	341	23624	4729	273	112575
Total	East	3648	71140	0	219	14912	5998	9105	696	16547	5562	301	128129
Total	South	22748	0	59715	1525	12156	3261	11199	18496	2014	13071	429	144614
Total	West	60940	76992	0	2041	31538	12179	8261	2207	9479	6214	770	210621
Total	DE	111559	149581	92127	4166	66971	25224	41557	21740	51664	29576	1773	595938

Table 2.18 shows the regional data on district heat generation in states in 2013 used for calibration. Heat generation data from other references is used for the 2013 calibration as well.

Table 2.18: District heat generation in states (regions) in 2013

State	Model region	Total	CHP	Renewables
		TJ		
Baden-Württemberg	South	52991	36864	11205
Bayern	South	55698	39730	8839
Berlin	East	46602	31930	3676
Brandenburg	East	26538	17285	3906
Bremen	North	6017	3890	1447
Hamburg	North	19720	11479	3236
Hessen	West	37944	27981	4479
Mecklenburg-Vorpommern	North	12320	7848	1678
Niedersachsen	North	28126	24195	2920
Nordrhein-Westfalen	West	120454	72419	6264
Rheinland-Pfalz	West	15709	9065	3455
Saarland	West	5720	2384	217
Sachsen	East	31468	21980	1080
Sachsen-Anhalt	East	36426	20191	5192
Schleswig-Holstein	North	24256	19554	2593
Thüringen	East	16361	9996	3223
Total	North	90440	66966	11873
Total	East	157395	101383	17076
Total	South	108688	76594	20044
Total	West	179827	111849	14415
Total	DE	536350	356791	63408

[13] Source: LAK-Energiebilanzen 2019 and own calculation

Techno-economic assumptions are based on the TIMES-PanEU model (Giannakidis 2010). However, the techno-economic data on main renewable technologies, namely wind and solar, are updated using BDI (Philipp Gerbert et al. 2018) as shown in Table 2.19.

Table 2.19: Techno-economic assumptions of the main renewable technologies

Technology	Investment costs [€/kW]					Fixed O&M costs [€/kW/a]					Technical lifetime
	2020	2030	2040	2050	2060	2020	2030	2040	2050	2060	
Ground mounted PV	650	550	500	450	400	16.3	13.8	12.5	11.3	10.0	25
Rooftop PV	1200	950	700	650	600	20.1	17.4	14.1	13.9	13.7	25
Onshore wind	1200	1100	1050	1000	950	11.2	11.3	12.3	11.5	10.7	25
Offshore wind North see zone 1	2900	2200	2100	2000	1900	43.0	32.9	31.0	29.7	28.5	20
Offshore wind North see zone 2	3455	2444	2266	2142	2018	52.2	37.0	34.1	31.7	29.4	20
Offshore wind North see zone 3	3883	2850	2629	2491	2353	58.1	43.0	40.1	37.8	35.5	20
Offshore wind Baltic	3469	2458	2280	2156	2032	65.1	49.0	45.0	42.7	40.4	20

Table 2.20 shows the assumptions on regional renewable technical potential and the availability of respective renewable resource. The assumptions for photovoltaic, onshore and offshore wind base on EuPD (2008) and JRC ENSPRESO (Ruiz et al. 2019) respectively. The data for offshore potential is taken from Rohrig et al. (2013), BSH (2017a) and BSH (2017b).

Table 2.20: Assumptions on regional renewable potential and availability

Technology	Overall technical potential [TWh]				Availability [%]			
	North	East	South	West	North	East	South	West
Ground-mounted PV	43	34	24	24	0.095	0.106	0.115	0.102
Rooftop PV	15	15	27	30	0.097	0.094	0.109	0.101
Onshore wind (Low speed)	6	31	38	17	0.191	0.177	0.173	0.178
Onshore wind (Medium speed)	43	81	18	28	0.242	0.229	0.223	0.230
Onshore wind (High speed)	121	11	0	9	0.340	0.260	-	0.264
Offshore wind (North see zone 1)	48	-	-	-	0.445	-	-	-
Offshore wind (North see zone 2)	70	-	-	-	0.491	-	-	-
Offshore wind (North see zone 3)	116	-	-	-	0.514	-	-	-
Offshore wind (Baltic see)	11	-	-	-	0.468	-	-	-

2.6. Other sectors

Other consumers such as agriculture, commerce and freight transport are more constrained, depending on the market trends and policies that are in effect (Baindur and Viegas 2011). To represent the entire energy system, other consumers are modelled in a simplified way using demand and emission scenarios. For agriculture and commerce the study on climate pathways for Germany (Klimapfade für Deutschland) by Philipp Gerbert et al. (2018) is used, which studies three different transition pathway scenarios for Germany's overall energy system.

These scenarios are Reference, 80% pathway (80% greenhouse gas reductions in 2050 in comparison with 1990) and 95% pathway. The results for the development of electricity, heat and hydrogen demands as well as emissions by agriculture and commerce (Germany GHD[14] sector) in the reference, 80% pathway and 95% pathway scenarios are used in this project for the REF, CTX and CFT scenarios respectively.

For freight transport the "DENA Leitstudie" study by Bründlinger et al. (2018) is used. This study investigates the integration of the German energy transition (Energiewende) until 2050. Several transition scenarios are considered in this study. The results for the development of electricity, heat and hydrogen demands as well as emissions by the freight transport sector in the reference, 80% technology mix pathway (TM80) and 95% technology mix pathway (TM95) scenarios are used in this project for the REF, CTX and CFT scenarios, respectively.

Finally, Table 2.21 shows the summary of demand and emission scenarios for other sectors which are used in this project as explained above.

Table 2.21: Demand and emission scenarios for other sectors (sector "Rest")

Commodity	Scenario	2013	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Electricity Demand [TWh]	REF	155	154	147	145	143	144	146	147	149	150	152
	CTX	155	154	149	149	148	151	153	154	155	156	157
	CFT	155	154	149	149	148	151	153	154	155	156	157
District heat Demand [TWh]	REF	17	16	22	23	24	25	25	24	24	24	23
	CTX	17	16	24	27	29	31	33	32	32	30	29
	CFT	17	16	24	27	29	31	33	32	32	30	29
Hydrogen Demand [PJ]	REF	0	0	0	0	0	4	8	12	15	21	28
	CTX	0	0	6	19	33	69	106	137	167	217	266
	CFT	0	0	6	19	33	69	106	137	167	217	266
GHG Emissions [kt]	REF	116007	109407	108037	101167	94297	87818	81338	76359	71379	63783	58188
	CTX	116007	109407	100696	84790	68883	54820	40758	32861	24964	20905	16845
	CFT	116007	109407	100696	84790	68883	48058	27233	13616	0	0	0

2.7. Coupling

In order to have a full picture of integrated energy system with enhanced representation of actors -taking into account the interactions between demand and supply side- the semi-automated soft linking interface to facilitate data exchange between the models are developed. The individual TAM modules describing industry, residential, passenger transport, supply and other sectors of German energy system are coupled through exchange of endogenously derived commodity demand and prices to reach equilibrium. It is analysed which price is endogenously

[14] Gewerbe Handel Dienstleistungen meaning Business, Commerce, Services (including agriculture)

derived at the demanded quantity of a particular commodity and how this price signal affects the optimal choices for decentralised options. This also brings new insights into the methodological approach for coupling of different models, which also seem to be transferable to other model couplings. One advantage of this methodology is: although the commodity prices are set endogenously in the coupling process, they are exogenous for each end-use sector model and therefore could be included in more sophisticated and realistic decision making processes such as budget constraints. Figure 2.30 shows the coupling process developed in this study.

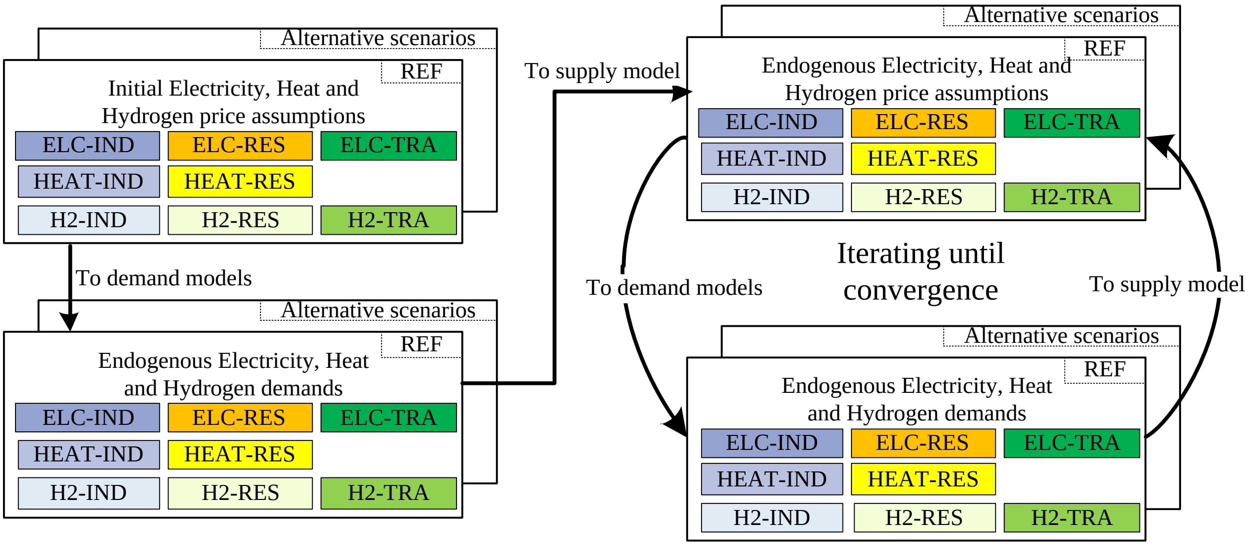


Figure 2.30: Schematic of the coupling process

2.7.1. Iteration procedure

First, the demand side models, i.e. industry, residential and transport, are run with an initial price assumption (shown in Figure 2.31) for electricity, district heat and hydrogen commodities in the reference and alternative scenarios.

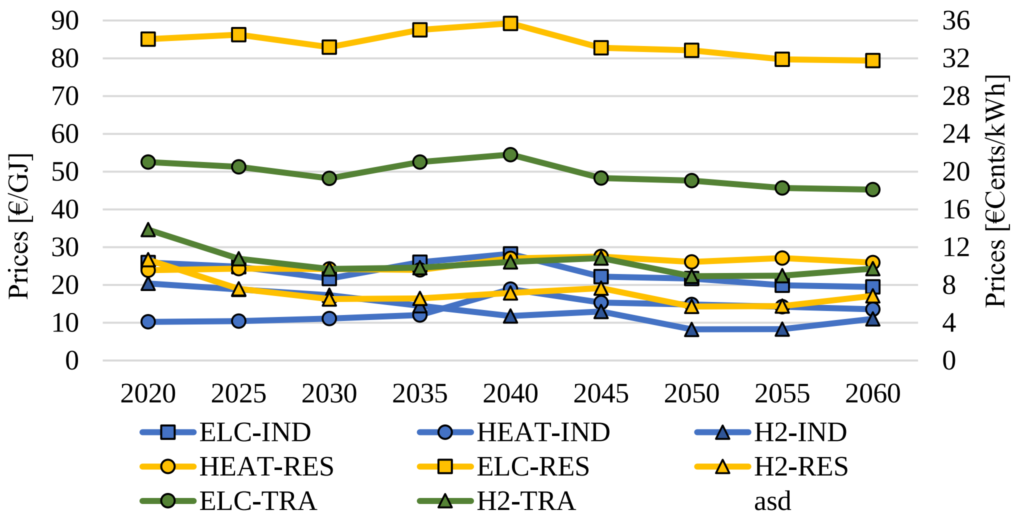


Figure 2.31: The initial electricity, heat and hydrogen prices in the reference scenario

Based on these initial price assumptions (P_0 in stage 0/1 shown in Figure 2.32), the output of the sectoral models would be an array of demands for electricity, district heat and hydrogen required by consumer actors in the industry, residential and passenger transport sectors (stage 1/0 in Figure 2.32) for meeting their energy service demands (production, heating, cooling, lighting, appliances and mobility) and technology profile on national level throughout the modelling horizon and export the results to the coupling repository.

Then the supply sector model reads the electricity, heat and hydrogen demands calculated by demand sectors from the repository. The technology profiles, energy carrier prices and respective emissions are determined through minimizing the objective function representing total system costs of the supply sector. It is then up to the overall model how to supply this energy carrier demand together with energy service demands of other sectors under the framework conditions (e.g., environmental policies) at least system costs, while considering heterogeneous but purely economic-driven decisions of the actors in supply, industrial, residential and passenger transport sectors.

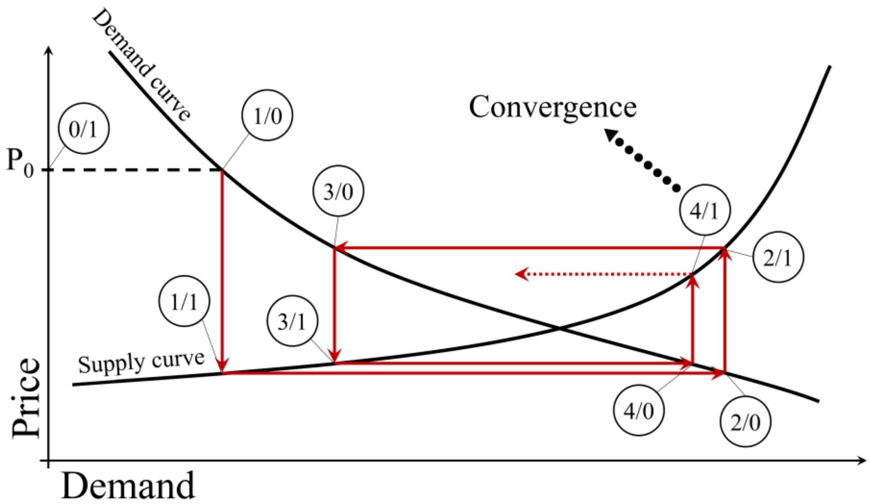


Figure 2.32: Simple iteration procedure on convex supply and demand curves

Furthermore, there will be new intermediary energy carrier prices , e.g. electricity, heat and hydrogen (stage 1/1 in Figure 2.32) together with availability and usage of resources (e.g., solar, wind, biomass, and etc.) exchanged between sector models. However, these prices differ from the initial price assumption P_0. In the second iteration, the demand side sectoral models read the electricity and heat prices and run the models to compute the new demands (stage 2/0 in Figure 2.32) . This bilateral data exchange between the models is iterated through further stages (e.g. 2/1, 3/0, 3/1, 4/0, 4/1, etc.) until the models converge and the errors of the price and demand arrays of two successive runs are lower than a user-defined threshold. To identify the desired threshold, special attention is paid to the run time of the models. This method is known as the simple Gauss-Seidel iterative method (Hegde 2015). In this method the speed of convergence and the number of required iterations are very dependent on the shape of the supply and demand curves as well as the starting point 0/1.

Equation 2.9 and Equation 2.10 show the mathematical formulation of the iteration termination conditions.

$$\left|Price_i - Price_{(i-1)}\right| \leq Err_{price} \qquad \text{Equation 2.9}$$

$$\left|Demand_i - Demand_{(i-1)}\right| \leq Err_{Demand} \qquad \text{Equation 2.10}$$

where:

$Price_i$	is the price array produced by supply model in the i-th iteration;
$Demand_i$	is the demand array produced by demand side models in the i-th iteration;
Err_{price}	is the user-define threshold for price error between two successive runs;
Err_{Demand}	is the user-defined threshold for demand error between two successive runs.

It is to be noted that the components in price and demand arrays are aggregated based on the fuel commodity, then these values are compared across the i-th and the (i+1)-th iterations. The coupling process could help us to investigate the operation and investment decisions of supplier and consumer actors towards energy transition.

2.7.2. Iteration method modification

A convergence with the simple Gauss-Seidel iterative method seems guaranteed as long as the curves are convex and there is an equilibrium point at the intersection of the curves. However, this can be violated due to the shape of the curves and the starting point even with convex curves and an existing equilibrium point as it also occurred during the actual coupling of models in this project. Therefore, an existing equilibrium does not mean that it can be easily reached through iterating sector models even though it is achieved easily in an integrated model.

We do not intend to go through a parametrical investigation of this, however just from a geometrical point of view we can consider how the divergence happens despite the existence of an equilibrium. For instance, in Figure 2.33 the curves and the starting point is just slightly changed. As it can be seen, in the second iteration at stage 2/0, continuing the normal iteration will lead to stage 2/1 and hence a divergence. However, if the demand at stage 2/0, which is fed to the supply curve, is slightly modified, the divergence will not happen. Therefore, instead of feeding the demand at 2/0 to the supply curve, a modified demand as a weighted average of the demands at 1/0 and 2/0 with an exemplified weight of 0.25 for the former and a weight of 0.75 for the latter will be fed to the supply curve which corresponds to the demand at stage 2'/1 and 3'/0. From stage 3'/0 the iteration is continued normally to stage 3'/1. However the iteration will not go through stages 4'/0, 4'/1 and 5'/0 since it will again result in divergence. From 3'/1 a weighted average of demands at 2/0 and 3'/1 with a weight of 0.25 for the former and a weight of 0.75 for the latter is calculated again so that the demand at 4"/0 is obtained. This method, which is called weighted Gauss-Seidel iterative method or relaxation in Gauss-Seidel iterative method, is continued until the convergence is reached.

The weight (i.e. 0.75 for the newly obtained demand in the example) is called the relaxation factor, which is not necessarily kept constant throughout the iterations as it was modified several time during the actual iterations in this project to facilitate the convergence.

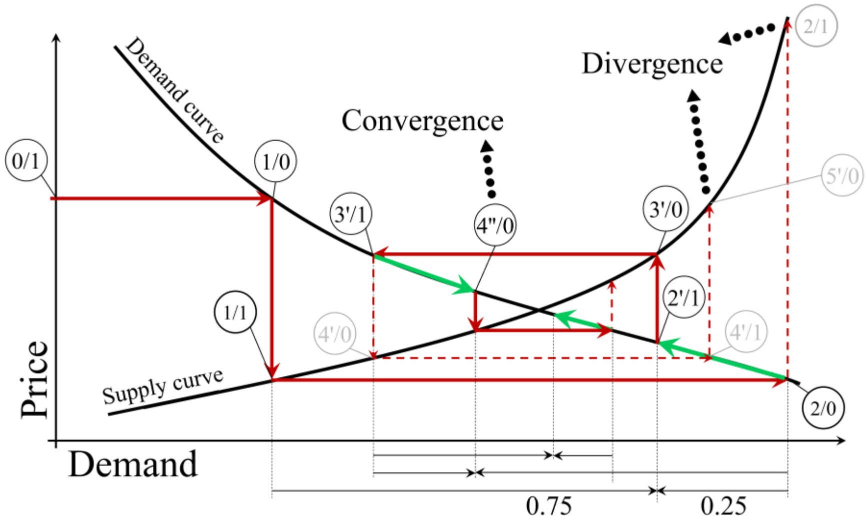


Figure 2.33: Modified iteration procedure on convex supply and demand curves

2.7.3. Consumer price components

It is to be noted that the energy carrier prices generated by the supply sector are the marginal costs of generation of the respective commodity, which is equivalent to its market price. In the reality there are some other cost elements which are added to the commodity market price for the end-user or retail price, which is actually seen by the consumer. For instance, the average electricity price in the electricity market in 2019 was about 3.8 Cents/kWh (Fraunhofer ISE 2020). After the distribution and marketing this price was about 7 Cents/kWh (BDEW 2020). However the electricity price for example for households in 2019 was 30.4 Cents/kWh (BDEW 2020). The difference includes value added tax, grid fees, renewable surcharge, concession fee, electricity tax, CHP and other surcharges, which is not generated endogenously in the model. Therefore, these cost differences are calculated for each sector separately and added to the electricity, heat and hydrogen prices produced by TAM-E-Supply as mark-ups to model the actual price the consumers see in each sector. These mark-ups are assumed to remain constant throughout the model horizon.

3. Policy scenarios

An increasing amount of information on the state of the market and the grid, combined with regulatory changes, may provide incentives for consumers to participate more actively and adapt to changes in generation or to support the grid (Bauknecht et al. 2020). Therefore, one reference scenario and three alternative policy scenarios are developed and tested to determine the effect on decentralisation of the German energy system and the necessary framework conditions. All scenarios include the methodological extensions of TAM described in Section 2 and other common assumptions such as nuclear and coal phase-out and are compared to the reference scenario. The prices and demands for the base year and statistical years (years before 2020) are constant based on historical data across all scenarios.

3.1. Socio-economic assumptions

The basic demographic and economic data used in the following scenario analyses is mainly adopted from the study *Projektionsbericht 2019* (Bundesregierung 2019) (cf. Table 3.1). Since the projections only extend to 2035, the values up to 2060 were extrapolated using a set of indicators based on further studies (BDI 2018; dena 2018).

From 2013 to 2060, the gross domestic product (GDP) of Germany is assumed to grow at an average annual rate of 1.2 %, with a downward trend over time. In the same period, Germany's population is expected to decrease by about 6 million inhabitants to 74.9 million in 2060 resulting in an increase in GDP per capita of almost 84 % compared to 2013. Due to the trend towards smaller household sizes, the number of households as well as the number of residential buildings in Germany will continue to increase until 2040. When aviation is not taken into consideration, the passenger transport volume only exhibits a further increase until 2045 and then drops again roughly to the level of 2035 as a result of the decline in population. With the expected on-going rise in air travel, however, total passenger transport volume still grows until 2060. The freight transport volume, on the other hand, which is mainly bound to the development of GDP, is assumed to rise substantially by nearly 54 % in the period from 2013 to 2060.

Table 3.1: Key socio-economic parameters for the scenario analysis[15]

		2013	2030	2040	2050	2060	Change (2013-2060)	Avg. Change p.a. (2013-2060)
GDP	Bn €$_{2010}$	2701	3445	3825	4235	4629	71.4%	1.2%
Population	M	80.6	82.6	80.9	78.0	74.9	-7.1%	-0.2%
GDP per capita	€$_{2010}$/cap	33490	41717	47295	54286	61773	84.5%	1.3%
Households	M	39.3	42.8	43.0	42.4	41.6	5.8%	0.1%
Residential buildings	M	18.5	20.0	20.3	20.3	20.2	9.2%	0.2%
Passenger transport volume	Bn pkm	1144	1580	1674	1726	1757	53.5%	0.9%
Freight transport volume	Bn tkm	617	808	879	917	953	54.4%	0.9%

Regarding the price projections for fossil fuels, the assumptions that have been laid down for the Sustainable Development Scenario in the World Energy Outlook 2018 (IEA 2018) have been chosen (Table 3.2). Again an extrapolation was necessary using the basic development from the Beyond 2°C Scenario (B2DS) of the Energy Technology Perspective 2017 study (IEA 2017). Thus, the world market price for crude oil decreases continuously from 67 US\$$_{2017}$/bbl in 2018 to 60 US\$$_{2017}$/bbl in 2060, corresponding to an increment of –10% in real terms. The declining demand for oil, triggered by climate protection efforts, limits the call on higher cost oil to balance the market and the price therefore stays "lower for longer".

Based on the global market prices, cross-border prices for Germany are calculated, resulting in a price decrease of –10% for crude oil and an increase of +2% for natural gas between 2018 and 2060. The decrease is expected to be more pronounced in the case of hard coal (–32%) based on the higher carbon content. For lignite, which plays a crucial role in electricity generation in Germany, the average full costs of lignite extraction in Germany are applied and assumed to be constant over the modelling period.

Table 3.2: Price assumptions for primary fossil fuels[16]

		2013	2018	2030	2040	2050	2060
Crude oil	US\$$_{2017}$/bbl	110	67	66	64	62	60
Cross-border prices							
Crude oil	€$_{2013}$/GJ	14.34	10.25	10.15	9.86	9.55	9.24
Natural Gas	€$_{2013}$/GJ	8.48	5.65	7.03	6.55	6.07	5.78
Steam Coal	€$_{2013}$/GJ	2.21	2.67	1.98	1.93	1.87	1.81
Lignite	€$_{2013}$/GJ	0.99	0.99	0.99	0.99	0.99	0.99

The future development of consumer prices of secondary fuels which are processed from the primary fossil fuels, especially oil products such as gasoline, diesel, LPG, fuel oil, etc., are dependent on the primary fuels prices. In order to determine that, linear regression analysis are carried out using historical data on both prices of primary fuels and consumer prices of secondary fuels. Using the regression line and the price assumptions for primary fossil fuels, the future development of consumer prices of the secondary fuels are calculated. Figure 3.1

[15] Based on *Projektionsbericht 2019* (Bundesregierung 2019)
[16] Based on the *Sustainable Development Scenario* from IEA 2018 and BMWi 2019

shows an example of regression analysis to determine secondary fuel price development for industrial light fuel oil.

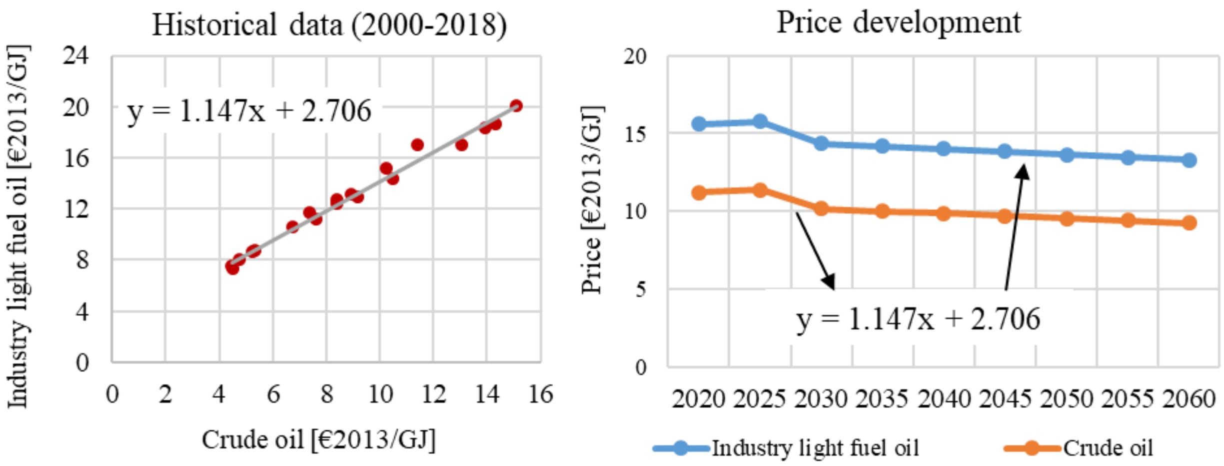


Figure 3.1: Regression analysis to determine secondary fuel price development

3.2. Reference scenario (REF)

The reference scenario (REF) represents the business as usual condition for the entire German energy system. This scenario is developed to depict the least-cost configuration of energy system under current energy and environmental policies. For instance, the nuclear and coal phase-out policies by the end of 2022 and 2038 respectively as well as slight increase of carbon prices are modelled in the reference scenario. The development of carbon prices for the reference scenario and other policy scenarios are presented in Figure 3.2. All other policy scenarios are developed on top of the reference scenario.

3.3. Carbon tax scenario (CTX)

This policy scenario allocates tax for emitting of CO_2. From the modelling perspective, the actors committing to CO_2 emissions should pay this tax. The assumption is based on the recommendations developed by Matthey and Bünger (2018) from German Environment Agency (2019) to consider the damage cost for climate change. In other words, the cost of a CO_2 tax in 2050 is assumed to be 240 Euro per ton of CO_2-equivalent (1% discount rate) interpolated and extrapolated to cover the modelling horizon.

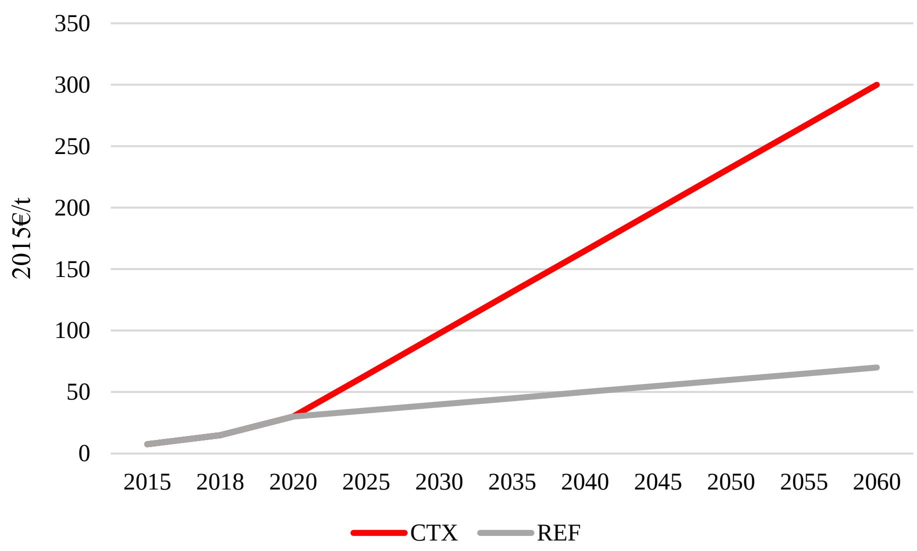


Figure 3.2: The development of carbon tax in policy scenarios

3.4. Reserved Capacities scenario variant (RCA)

In addition to fulfilling the electricity demand throughout the year, the transmission grid operators are responsible to ensure the availability of enough reserve capacity for the electricity demand from the grid at each time segment for the sake of security and reliability of electricity supply. For this purpose a peaking constraint is formed within the TAM-E-Supply model for all scenarios, which ensures the availability of enough dispatchable reserve capacity. However, since the dispatchable capacity within the industry can also contribute to the overall reserve capacity, the RCA scenario was developed.

From the modelling perspective this is implemented by including the capacities of industry's generation technologies in the peak constraint as well as industry's overall electricity demand including the part that is fulfilled by self-generation. In other scenarios the supply sector is responsible for providing the reserve capacity only for the grid demand.

The reserved capacity scenario is developed on top of the carbon tax scenario and always run along with it. This scenario is thus developed as a validation scenario to ensure the two approaches towards ensuring reserve capacity do not lead to dramatic differences in the results. Therefore, the results of this scenario were checked against the results of the carbon tax scenario for any significant differences. Since they were not different, it was concluded that both approaches are valid. Therefore the results from RCA are not shown further in the study.

3.5. Carbon-Free Target by 2050 and beyond scenario (CFT)

This scenario is developed based on German decarbonisation target by 2050 recently emphasised and debated in the UN climate summit in 2019 (EURACTIV 9/24/2019). In this scenario we investigate if decarbonisation targets by 2050 could be met in different energy sectors of Germany and analyse these until 2060, taking into account the total system costs required for meeting the carbon-free targets. Because a complete decarbonisation in the industry sector is not achievable, a carbon cap based on the technical minimum possible level for both energy and process-related emissions was implemented in this sector. All other sectors were set to produce zero emissions by 2050. The carbon prices in this scenario are identical to the prices in the reference scenario.

4. Results

4.1. Coupling process

The coupling process exchanges data between models in an iterative manner for each scenario reaching convergence after maximum 14 effective iterations, after all necessary model adjustments were undertaken. The iterations ended when an acceptable level of error below 5% across two successive iterations is reached, as described in Section 0. Convergence barriers are resolved through model improvements and the iterations would begin again at this new starting point, thereby achieving convergence faster.

4.1.1. Iteration Procedure

The iteration procedure itself was repeated until convergence was reached across all sectors for the three commodities exchanged (electricity, heat and hydrogen). Figure 4.1 shows a basic timeline of the iteration procedure as well as the challenges encountered (circles) and the steps taken to improve the exchanging process (arrows). In general, fluctuations in demands were critical to the convergence and highlighted the sensitivity of the sector models to changes in demands in other sectors for fuels used in their own sectors since the higher demand would drive prices up or down. As prices decreased for a specific commodity, it was inevitable that the sector models would increase their demand in the next iteration, which would lead to an increase in prices from the supply side in the following iteration, which in turn would lead to a decrease in demand in the demand sectors in the iterations following this one. This would continue if interventions were not undertaken to flatten the curve and so a relaxation factor was introduced as described in Section 2.7.

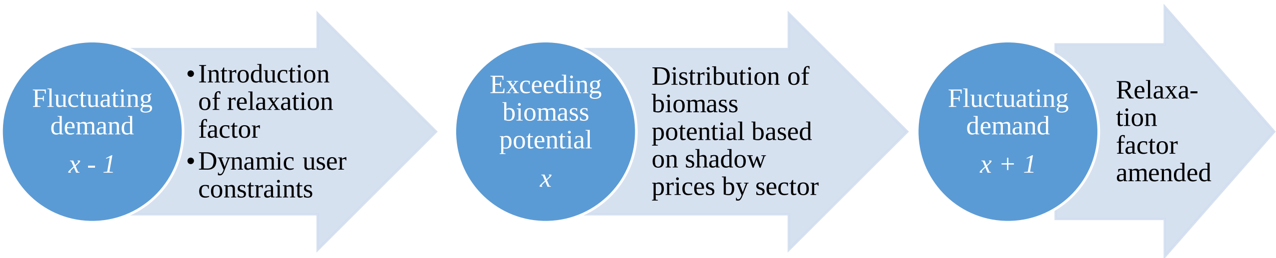


Figure 4.1: Timeline of iteration procedure and iteration adjustments undertaken

Initially, the demands from the previous iteration (*x-1*) and the new demands arising from the new prices in the next iteration (*x*) would be averaged using user-specified weights (relaxation factors) and provided as the new starting point for the next iteration (*x + 1*). The impact of the relaxation factor allowed lower fluctuations across and between sectors and specific energy carriers.

The national biomass potential was initially not exceeded, but due to the correction of the fluctuating demand it was exceeded in subsequent iterations. Therefore, it was necessary to distribute the potential available to the different sector models. This was done by assessing the shadow prices (overall marginal abatement costs) for the zero carbon emission constraint of each sector in the CFT scenario and redistributing the potential to the point where the cost to decarbonise was fairly even for each sector as shown in Table 4.1. The starting point revealed a wide range of shadow prices across supply, industry and households. Since carbon-free transport fuels (electricity, hydrogen) are produced by the supply sector, the initial reduction of the biomass potential allocated to the supply sector in favour of industry and households was again increased in the third distribution. The final distribution of the maximum biomass potential included 300 PJ for the supply sector and 450 PJ each to industry and households.

It is interesting to note that sometimes reducing the share of overall biomass potential available to a sector (e.g., industry) might cause also an unexpected decrease in the shadow price of the carbon emission constraint. This might be due to the fact that a decrease in the biomass potential of a demand sector , e.g., industry, means an increase in the biomass potential of the supply sector since the overall biomass potential is constant. This results in lower electricity, heat or hydrogen prices generated by the supply sector. These lower prices of the commodities, that play a key role in industry's emission reduction through electrification or fuel switch, means cheaper "decarbonised energy carriers" for the sector through centralised generation rather than decentralised generation within the industry, which in turn leads to lower shadow prices of carbon emission constraint. This means that there should be an optimal point of decentralisation in the overall energy system.

Table 4.1: Distribution of biomass potential across demand sectors via shadow prices

		Supply	**Industry**	**Households**	**Total**
Starting point	max biomass potential (PJ)	515.0	375.8	605.1	1,495.9
	€/tonne CO_2	1,097.4	3,741.6	519.6	
First distribution	max biomass potential (PJ)	150.0	550.0	500.0	1,200.1
	€/tonne CO_2	9662.6	2,637.9	1,564.6	
Second distribution	max biomass potential (PJ)	300.0	450.0	450.0	1,200.0
	€/tonne CO_2	3,773.5	3,530.8	2,796.0	
Final distribution	max biomass potential (PJ)	300.0	450.0	450.0	1,200.0
	€/tonne CO_2	3,773.5	3,530.8	2,796.0	

Following this, it became evident that a further modification of the relaxation factor should be introduced to the iterative method to decrease the number of iterations to achieve convergence (see section 2.7).

4.1.2. Price and demand development across (selected) iterations

Through the iteration process the energy prices respond to the demands and are reflected in the exchange procedure not only within each sector but also in response to the demand fluctuations in other sectors. Figure 4.2 shows the development of the household electricity prices for selected iterations from 2020-2060 in the reference (REF) and the carbon tax (CTX) scenarios as an example. The results show that by increasing the number of replications, the prices get closer. The scenarios converge in the same iteration. The electricity price in the REF scenario undergoes the greatest leap from 2035 to 2040, whereas the electricity price in the CTX scenario fluctuates more to reflect the investment changes required to make the final shift towards a specific energy carrier. The convergence for the scenarios is shown in black, where the error is less than 5% and consistently below this level across all sectors and for the other prices and demands of all exchanges. This stable performance of sector models with regards to iterative changes in price and demand points to the fact that each sector model follows a certain price-demand elasticity, which otherwise could not be shown in an integrated model.

Figure 4.3 illustrates the electricity, heat and hydrogen prices calculated endogenously for industry, household and transport demand sectors for the CTX scenario across the modelling horizon. The demands for electricity and heat are similar across the REF and CTX scenarios, differing only in terms of the price patterns. The electricity prices in the REF scenario remain fairly constant, whereas in the CTX scenario the electricity prices increase for all consumer groups from 2035. This indicates a shift towards a decarbonised energy system in an effort to avoid higher energy prices associated with the carbon tax, which includes a higher demand for electricity and district heat. Once a certain level of decarbonisation has been achieved, after 2045, the prices decrease again slightly and stabilise due largely to the minimal variable costs of renewable power generation.

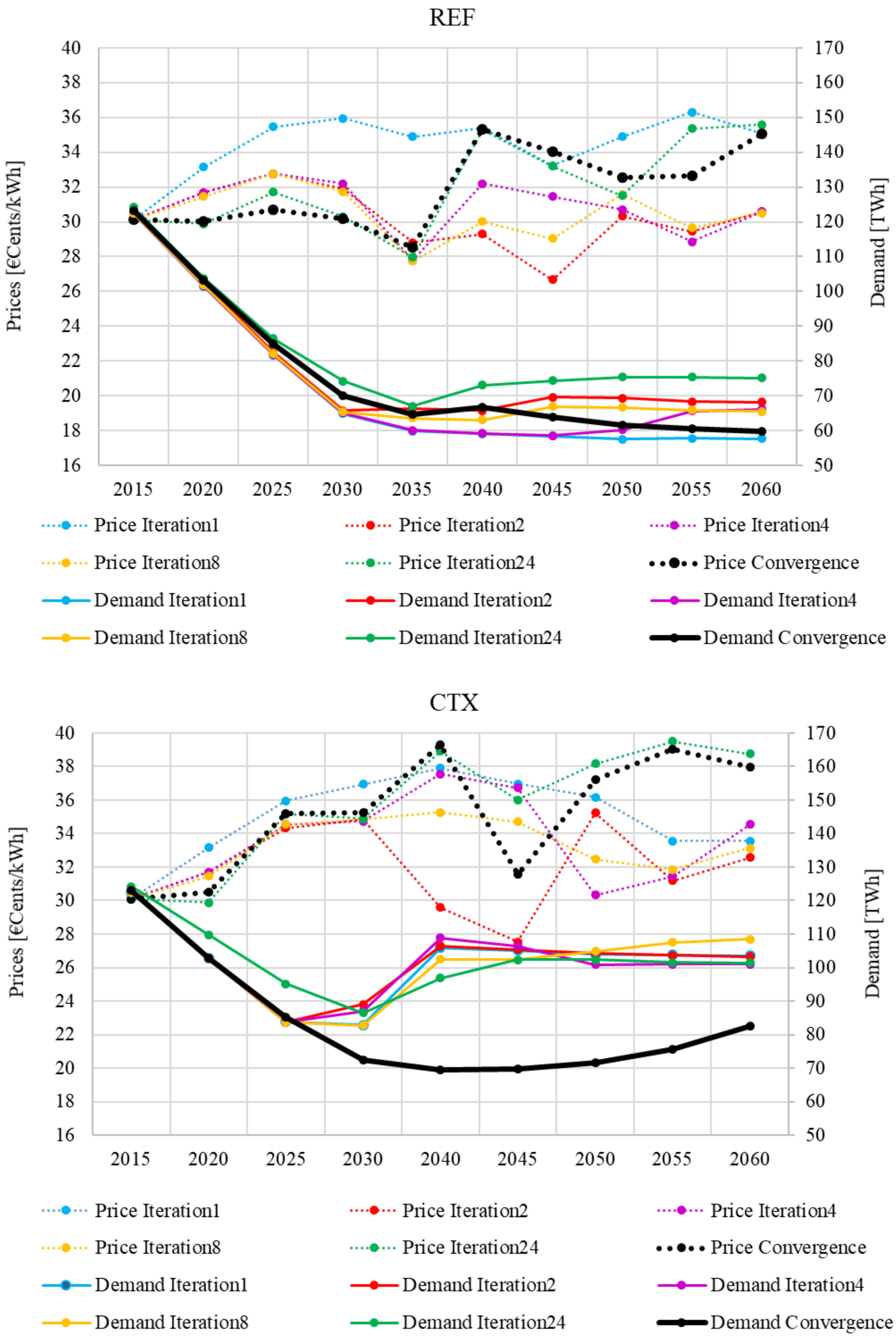


Figure 4.2: Development of electricity prices for households by iteration sequence in the reference and carbon tax scenarios

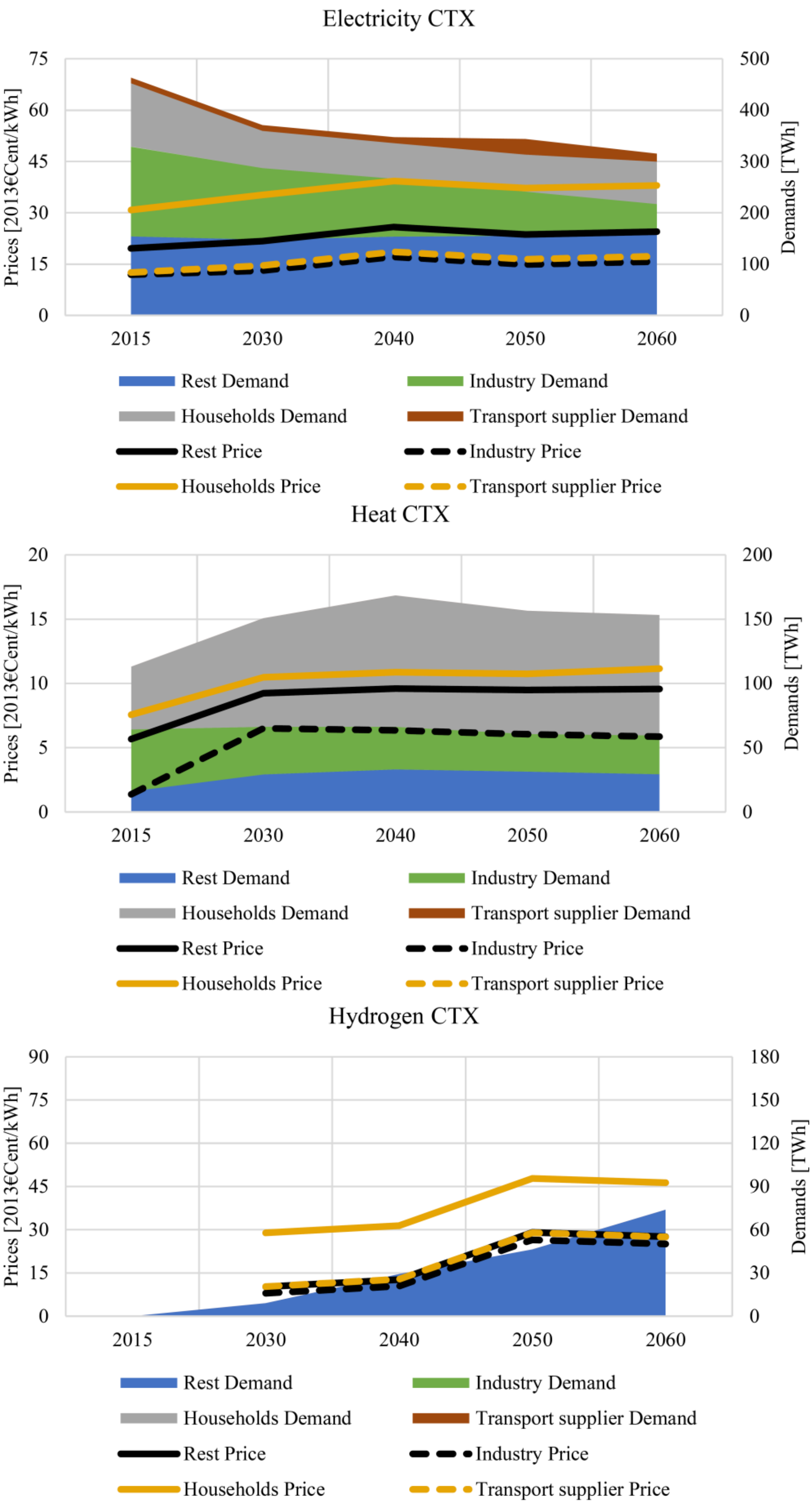


Figure 4.3: Electricity, district heat and hydrogen prices and demands after convergence is reached for industry, household and transport demand sectors in the CTX scenario

4.2. Scenario analysis

4.2.1. Comparison of the TAM with the aggregated model

Validation of the TAM methodology is provided through an assessment of the results from the reference (aggregated) model and the TIMES Actors Model (disaggregated, TAM). The value in this methodology lies in the expansion of the actors in the supply and demand sectors. This allows the consideration for smaller actors and the influence of diversified demand and investment opportunities from a heterogeneous range of actors. The methodological improvements in the TAM (the disaggregated model) can be compared to the aggregated model through the results. Taking one scenario as an example, the CTX scenario, we compare the differences in the total energy carriers, emissions per sector and the degree of decentralisation. The CTX scenario is selected for illustrative purposes and includes a carbon tax allocated to the production of CO_2 increasing to 240€ per ton of CO_2 in 2050. Between the aggregated and TAM models, differences can be observed in the total overall energy, emissions per sector and the degree of decentralisation. More detailed sector-specific results are provided in Section 4.3 and a short overview is provided below.

For example, in the industrial sector, the aggregated model overestimates the degree of the decentralisation potential. This is due to the implementation of different electricity prices to the different actor groups in TAM. Here the actor groups with lower electricity prices do not perceive investments in self-generation as cost efficient. Production technologies deployed vary significantly between models due to diverse factors such as the unique production state of the different actor groups at the base year, their unique investment options and the different electricity pricing levels. Moreover, newly implemented technologies in TAM provides the industrial sector with more opportunities to reach decarbonisation targets.

In the household sector the aggregated model reflects an increased consumption by 15-20% between 2025-2040 for heating and water heating with higher overall demand for biomass and district heating. TAM, however, shows that the cost-optimal solution would rely on solar thermal longer but shift to district heating sooner. These differences are owed to the finer lens on the different building types and their occupants (owner vs. tenants), reflecting decision-making power, as well as their location (urban vs. rural) and the related access to specific energy carriers and technologies, as well as the financial capacity of households to afford the high upfront costs of investments. Without considering the heterogeneity of the actors as well as their ability to access and afford different investments means the carbon tax has a greater impact in the aggregated model. A shift in investment typology is not as easily made once the high upfront costs of investments in the cost-optimal solution have been made. Additionally, TAM offers an insight into the tenant sector, who have no decision-making power to invest in lower carbon - and costly - technologies. In 2050, CO_2-eq emissions are 40% higher in the aggregated model. With the majority of households living in multi-family homes as tenants, the greatest heating demand comes from this sector. However, this potential could remain untapped if decisive steps are not taken to encourage the investment of PV for landlords, which is the prevailing trend in both TAM and the aggregated model.

Unlike the aggregated model which has exogenous demand for each single transport mode, TAM-Transport (the disaggregated passenger transport model) provides free competition between travel modes, which could be done in the original aggregated model, TIMES-D (Haasz 2017a), only exogenously. Therefore, it can be seen in the results of TAM-Transport how a mode replaces another mode, as long distance fast trains replace all of the domestic aviation in the CTX scenario. Furthermore, thanks to the income group disaggregation, it can be seen only in the disaggregated TAM-Transport how different policy scenarios affect the transport behaviour of the passengers based on their income. For instance, on the one hand, the public transport share in fulfilling the transport demand of the lower income groups will grow significantly as these income groups have little or no budget to invest in new private cars or pay the high carbon taxes in the CTX scenario in addition to the fuel price and the car’s fixed costs. On the other hand, the higher income groups shift more towards using their private cars since they can afford it and the capacity of the public transport is mainly used by low income groups.

The high carbon taxes in the CTX scenario make power generation from fossil energy carriers prohibitively expensive in both model versions, leading to a rapid decrease. Therefore, most of the differences between the two models are seen in renewables especially onshore and offshore wind as well as ground-mounted PV (utility scale) and hydro. There is less electricity generation from onshore wind in TAM-E-Supply -the disaggregated supply sector model)- (around 31 TWh -15%- in 2050) and significantly more generation from offshore wind (up to 16 TWh -46%- in 2045). This emphasises the substantial role of new actors (i.e., institutional investors) with lower return expectations which works more in favour of offshore wind. On the other hand, the untapped potential of hydro energy (ca. 3500 TWh) as well as geothermal energy (around 10 TWh) are utilised only in TAM-E-Supply where these capital intensive technologies are less of a barrier to actors with lower hurdle rates. In general, the emissions do not differ much between the reference and TAM model versions in the CTX scenario. This is mainly due to the high taxes set in this scenario which makes use of fossil energy carriers prohibitively expensive. However, the emissions are slightly less in the aggregated model version especially in the beginning years when there is still large power generation from fossil fuels. This is mainly due to the fact that interregional transmission losses are not accounted for in the aggregated version. The level of decentralisation is higher in TAM since the new actors with lower return expectations considered only in this version such as institutions and especially energy cooperatives, have access to decentralised generation technologies which can be used on a local level (with the exception of offshore wind for institutions). This is because an important driver for these actors to invest in renewable or efficient CHP technologies is the creation and retention of value within local economies. Therefore, the decentralised technologies are preferred more in the aggregated model.

4.2.2. Cross-sectoral degree of decentralisation

Overall, the objective of the scenario analysis, as described in Section 3, is to assess the drivers and their influence on the overall degree of decentralisation in the energy system. A comparison of the self-generation of electricity across all sectors shows that in all scenarios rooftop PV plays the greatest role with the greatest contributions coming from the household and other sectors (agriculture, commerce, freight transport). Without the pressure of eliminating carbon from the energy system as in the CFT scenario, coal represents a constant source of self-generation in the industrial sector, whereas in the decarbonisation sector the focus shifts to harness industrial renewable waste. Bioenergy and onshore wind feature more in the decarbonisation scenario where carbon-free options are required to meet the targets.

Comparing the overall the degree of decentralisation in the demand sectors in terms of the share of electricity produced as a share of the total generated electricity in 2050 highlights that decarbonisation is not necessarily achieved through self-generation of electricity as evidenced that the lowest share of decentralisation (26.5%) occurs in the CFT scenario and the highest in the reference scenario (43.3%).

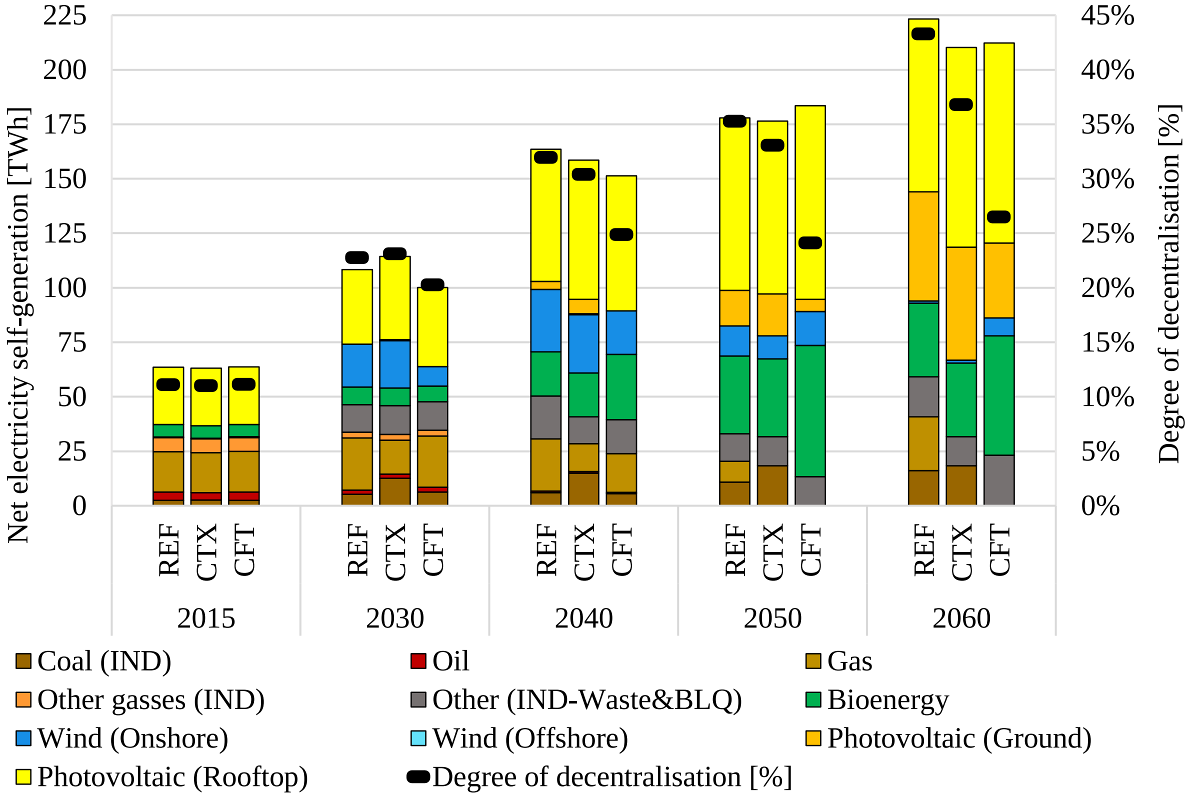


Figure 4.4: Scenario comparison for self-generation by demand sectors and the overall degree of decentralisation

The least-cost solution under the reference scenario indicates that the total self-generation in Germany increases from 63.57 TWh in 2015 to 223.2 TWh in 2060 indicating a 251.1% increase. This trend is coupled with an overall decrease in the total electricity consumed in the demand sectors by 17.1% in 2060 (515.7 TWh) compared to 2015 (516.7 TWh). Despite the financial disincentive of the carbon tax in the other scenarios - CTX, CFT – the overall increase in the self-generation is at a similar range at 230.6% and 233.8%, accounting for a total self-generation of 210.2 TWh and 212.2 TWh, respectively. However, due to the overall nature of the fuel mix in the demand sector which varies by scenario, the overall degree of decentralisation is lower in the CTX and CFT scenarios where the overall shares of electricity self-generation in the REF, CTX and CFT scenarios exhibit 43.3%, 36.8% and 26.5% decentralisation, respectively. Figure 4.4 clearly shows that the degree of decentralisation in each year is lower in more strict environmental scenarios although the absolute self-generation does not vary as much. The reason for this is the fact that there is more overall electricity demand in CTX scenario than the reference scenario and more in CFT than both reference and CTX scenarios (as shown in Figure 4.3) due to more drastic decarbonisation measures, while the self-generation is restricted.

Among the above mentioned measures for decarbonisation especially in the CFT scenario, there are higher levels of electrification as well as fuel switching to decarbonised energy carriers, such as hydrogen and district heating, which are mainly or at least partly produced from electricity. Nonetheless, the sectors have limited ability to produce electricity for own consumption mostly because of restriction in financial resources, which should also be used for other measueres such as efficiency improvements or investments in new technologies to replace the old ones. That's why the growth of self-generation from year to year is limited. On the other hand, the electricity demand growth at the same pace if not faster than the growth of self-generation to reach the decarbonisation target by 2050. Therefore, in the CFT scenario the degree of decentralisation almost stagnates. This indicates that although the energy sector will become more decentralised than today, the degree of decentralisation will not grow more than a certain range (here approx. 25%) if a carbon-free energy sector is to be achieved. There will be much more electricity demand in the demand sectors than their ability to self-generate. As a result, the energy system will still stay mainly centralised though more decentralised than today. Hence the requirements of a mainly centralised system will stay in place such as a widely developed electricity grid across Germany.

Taking a closer look at the distribution of self-generation across sectors in overall self-generation reveals that industry carries the largest share in all scenarios, but this share decreases from 67.1% in 2013 to 41.7% in 2060 in the reference scenario. The transport sector begins with self-generation from 2020 in all scenarios and surpasses the households share in 2030 with households producing 15.5 TWh in 2030 in the reference scenario accounting for 14.3% whereas the transport sector generates 19.6 TWh accounting for 18.1% of the total self-generation. However, this trend reverses again from 2045 due to the greater access to and investment in rooftop PV with households self-generating 35.5 TWh accounting for 20.2%. Similarly, the other sectors (Rest = agriculture, commerce, government) surpass the transport sector in 2045 in the reference scenario where the other sectors (Rest) self-generate 37.4 TWh of electricity accounting for 21.3% and with the transport sector self-generating 35.3 TWh accounting for 20.1%. A detailed view into the self-generation of the specific sectors is provided under each sector in Section 4.3.

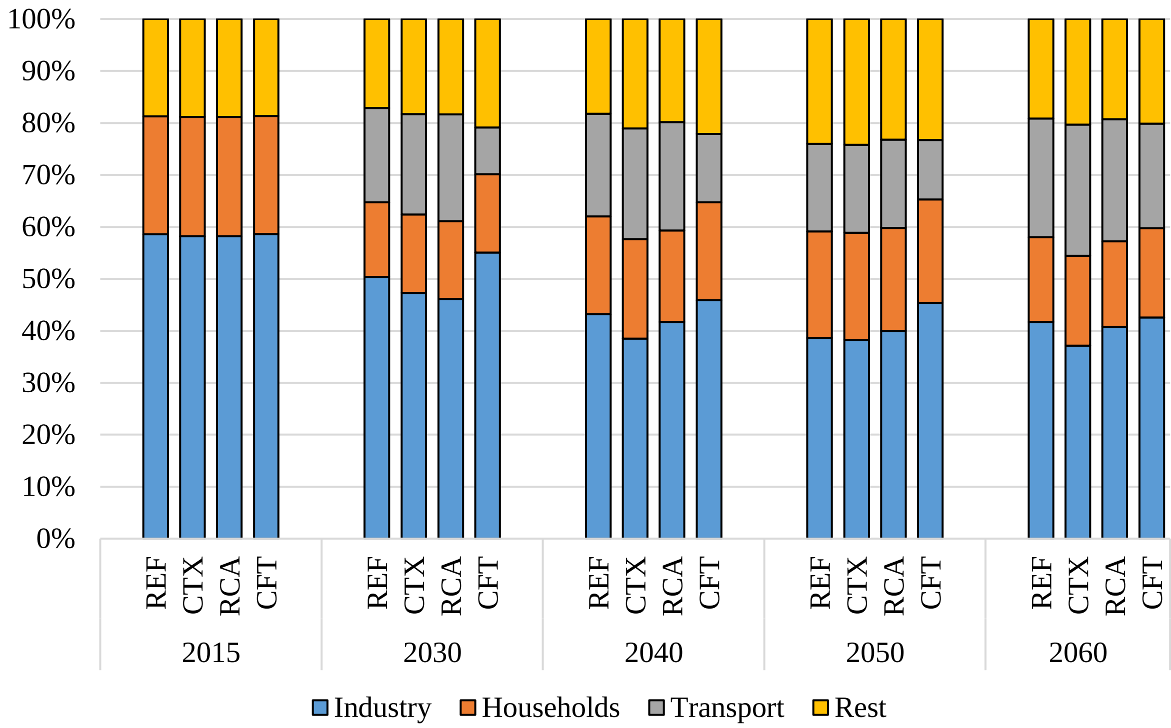


Figure 4.5: Share of self-generation by sector and scenario

4.2.3. Cross-sectoral CO_2 emissions

Decarbonisation is a key objective of the energy transition and therefore important to evaluate in which sector and how this objective can be achieved. The evolution of the shares of the total CO_2-equivalent emissions by sector compared to 2013 are presented in Figure 4.6. These results show that the CO_2-equivalent emissions of the modelled sectors reduce overall by 70%, 79.8%, and 95.2% in the reference (REF), carbon taxes (CTX), and carbon-free targets (CFT) scenarios, respectively, in 2050 compared to 2015.

Within each sector, the total reduction in total CO_2-equivalent emissions show that supply sector is able to decarbonise by 93.7% in the reference (REF) scenario by 2040 compared to 2013 In the demand sectors the industrial process and energy emissions reduce by 45.2% and 68.3%, respectively, and the household sector decarbonises by 57.8%. However, the transport providers, suppliers and rest decarbonise by 28%, 34.3% and 29.9%, respectively, indicating the limited ability to cost-efficiently replace fossil fuels and conventional with carbon-free alternatives. The industrial sector is very difficult to decarbonise due to the nature of the production processes. Some emissions in the industrial sector are also process-based and not as a direct result of energy consumption, therefore, the CO_2 emissions of the industrial sector is split into process-based and energy-related emissions.

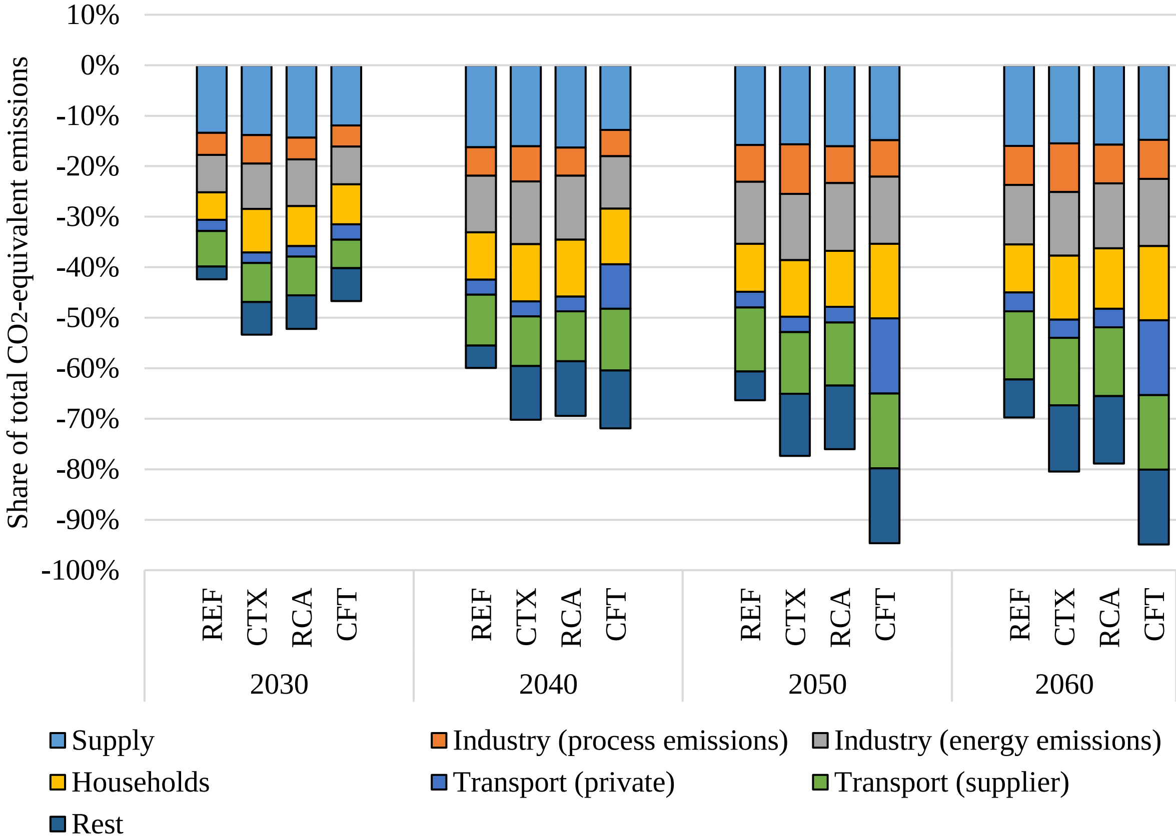


Figure 4.6: Shares of total CO_2-equivalent emissions by sector compared to 2015

With strict carbon-emission restrictions in place as in the CFT scenario, in 2050 the supply, industrial processes, industrial energy, household, transport private and transport suppliers are able to decarbonise by 99.9%, 61.4%, 90.7%, 99.7%, 100%, and 99.8% compared to 2013, respectively, which are achieved through demand reduction and shifting to carbon-free alternatives in all sectors, where possible. These results emphasise the role of carbon capture technologies in the industry sector as reductions of CO_2 emissions are largely due to investments in carbon capture technologies. Otherwise, due to limited technological alternatives, process-based CO_2 emissions are difficult to eliminate entirely, but energy-related emissions can be reduced by over 153 Mt. Households are able to decarbonise through the greater implementation of heat pumps (51% of total final demand), biomass (24%) and district heating (18%) to meet energy needs. While the transport private is only able to decarbonise by shifting wholly to electricity (74% of total final demand) and hydrogen-based (26%) vehicles, this will only be accomplished through both technological and behavioural changes (e.g., modal shift).

With the implementation of a carbon tax (CTX), the emission reductions are less strong indicating that total decarbonisation will require significant investments to enable a decarbonised energy system. In the CTX scenario in 2050, the supply, industrial processes, industrial energy, household, transport private and transport suppliers are able to decarbonise by 98.5%, 55.3%, 77.5%, 62%, 29.5%, and 64.6% compared to 2013, respectively, highlighting the room to improve emission reductions in all demand sectors. While the increased carbon tax acts as a necessary disincentive and does encourage investment in more carbon-free technologies, the CTX scenario will result in 82.8 Mt CO_2-equivalent emissions less and the CFT scenario in 213 Mt CO_2-equivalent emissions less compared to the REF scenario. The industrial sector reduces carbon emissions mainly through investments in energy efficiency and demand reduction from coal and gas-based production technologies. In the household sector, the reduction comes from consuming less gas and shifting to include ambient heat pumps into the fuel mix. The financial disincentive results only in the reduction of diesel vehicles (20.3 PJ in REF compared to 2.3 PJ in CTX in 2050) in favour of LPG-based vehicles.

4.3. Sector-specific results

This section provides more detail into the results from the sector-specific models: TAM-Industry, TAM-Households, TAM-Transport and TAM-E-Supply .

4.3.1. Industry

This section assesses the new insights gained from the new methodology in TAM. The TAM methodology applied to the Industry sector as described in Section 2.1 and 2.2.2 is compared with the aggregated model and analysed. As a complete decarbonisation is not possible in the industrial sector, the CFT scenario for this sector consists of an upper carbon cap. The value for the carbon cap implemented was the lowest technical possible emission level by 2050 at 15 million tons of CO_2 for energy related emissions and 22 million tons of CO_2 for process related emissions.

Results in the TAM-Industry model

For all scenarios in TAM-Industry, we can see an overall decrease in energy intensity and CO_2 emissions in the industrial sector as seen in Figure 4.7. Fossil fuels such as coal, coke, natural gas and oil decrease over time although not completely, even for the CFT scenario. This is due to the fact that some industrial processes cannot be fully electrified or a complete substitution of fossil fuels with renewable sources is not possible mainly due to requirements for high temperature heat. Biomass plays bigger role in CFT scenario. Here, the complete available biomass potential is employed, thus bringing to light that access to biomass for the industrial sector will have an impact on the decarbonisation potential of this sector. Despite higher energy intensity in the CFT scenario, emissions levels in 2050 and 2060 are lower. This is explained by larger investments in carbon capture technologies for this scenario.

Emission intensity is also on a downward trend for all scenarios. By 2050, emissions levels decrease by 55% in REF, 69% in CTX and 73% in CFT based on 2015 levels. Although CFT scenario results in the lowest emissions levels by 2050, the carbon tax implemented in CTX scenario is more efficient at decreasing emissions earlier.

In general, self-generation increases in comparison with 2015 levels due to high electricity prices. Hence, a higher degree of decentralisation can be observed for all scenarios with the exception of CFT scenario in 2050 and 2060. The emission cap is so low that it does not allow for any fossil fuel- based self-generation. This, together with limited availability of biomass, results in the lower decentralisation level. Therefore, we can infer that for deep decarbonisation, the industrial sector will more reliant on provision of electricity and heat from the supply sector.

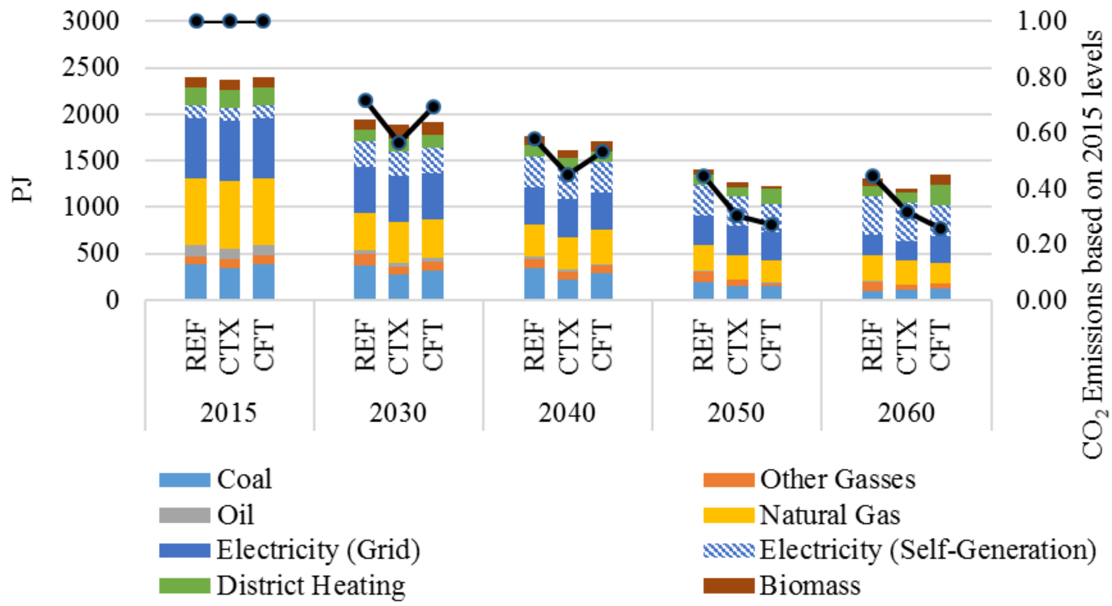


Figure 4.7: Final energy consumption by energy carrier in TAM-Industry for the different scenarios, 2015-2060

As previously mentioned, self-generation increased over time for almost all scenarios, however there are differences in the energy carriers used for self-generation as seen in Figure 4.8. From 2050 on, natural gas is no longer used for scenarios CTX and CFT. By 2050, self-generation in CFT is 100% renewable-based, as the model does not have sufficient carbon budget to make use of fossil fuel-based self-generation technologies. Therefore, availability of renewable energy sources such as biomass is a critical factor in the decentralisation potential for industrial actors under strict emission reduction targets.

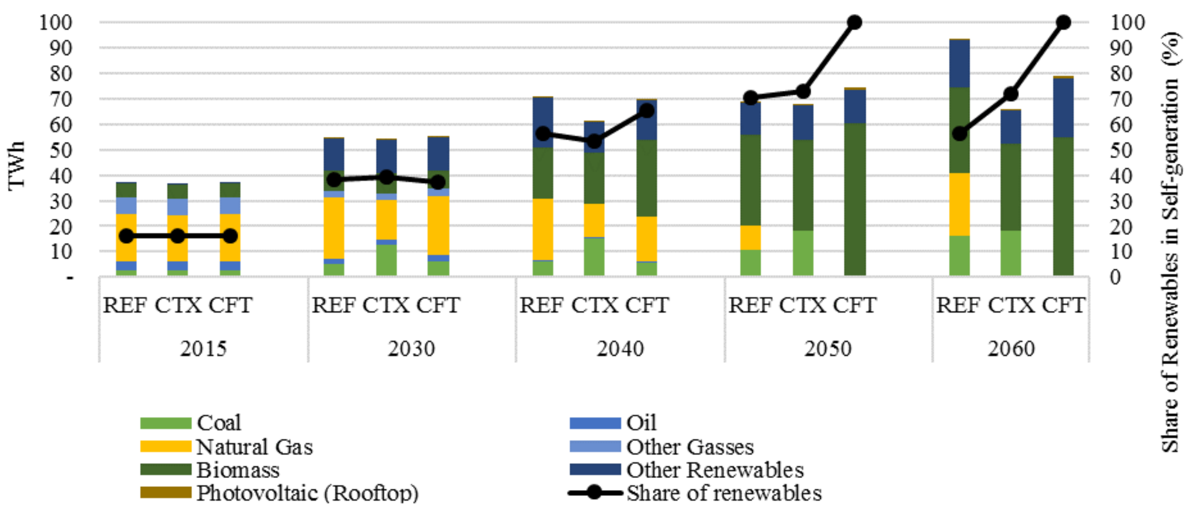


Figure 4.8: Electricity self-generation in TAM-Industry by source for the different scenarios. 2015-2060

Comparison of results in TAM-Industry and the aggregated model

In order to better understand the roles of individual actor groups in an industrial branch, Iron and steel industry will be the focus of the discussion in this section. Due to the increased availability of investment options in the TAM-Industry model compared to the aggregated model, the carbon cap that could be achieved in the TAM-Industry for the CFT scenario in the Iron and steel industry model was lower at 9 million tons compared to 10 million tons of CO_2 in the aggregated model.

For this industrial branch, carbon taxes in the CXT scenario seem to have little impact in the overall final energy consumption for both the TAM-Industry and aggregated model when comparing with the REF scenario as seen in Figure 4.9. Here, we can derive that the carbon tax implemented in CTF did not generate a large enough incentive a higher decarbonisation level beyond that of to the already expected emission pathway based on the REF scenario. From this, we can deduce that decarbonisation in the iron and steel industry is a cost-intensive process.

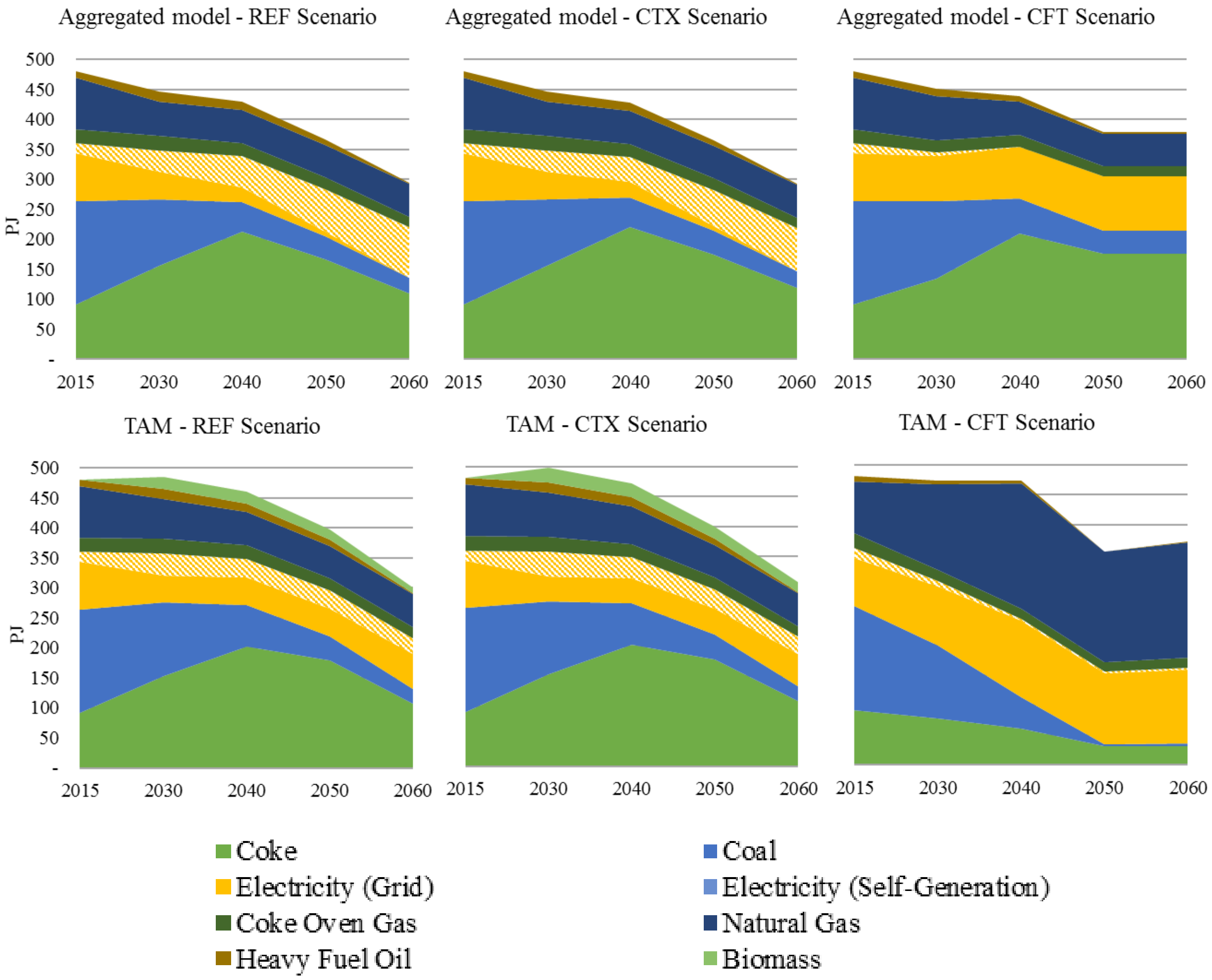


Figure 4.9: Comparison of final energy consumption for the Iron and Steel Industry in the aggregated model (top) and TAM-Industry (bottom) by energy carrier in the CTX scenario, 2015-2060

Regarding the development of the energy carrier mix for scenarios REF and CTX between the two model methodologies, some differences can be observed. In the aggregated model, REF and CTX scenarios, electricity demand towards the supply sector decreases over the years until the iron and steel industry is completely decentralised by 2060. In the TAM-Industry model, a reduction in electricity demand towards the supply sector can be observed from 2015 to 2030. After that, however, demand stays relatively constant until 2060. The reason for this difference lays in the different electricity prices for the different actor groups. The average electricity price in the aggregated model is high enough so that investments in self-generation result in lower production costs. For the actor group with the lowest electricity price in TAM-Industry (lower than the average price in the aggregated model), the price is low enough so that is preferable to simply buy electricity from the supply sector rather than self-generate. Hence, under the electricity prices provided from the supply sector model and carbon tax levels, the aggregated model shows a higher degree of decentralisation than TAM-Industry for both REF and CTX scenarios.

The major differences observed in Figure 4.9 correspond to the CFT scenario. Since self-generation options provided for the iron and steel industry rely mainly on non-renewable energy carriers, self-generation is not possible given the carbon cap implemented for both models. Therefore, all electricity consumption in this industry is provided by the supply sector. This leads to the conclusion that, for strict decarbonisation targets in industries with limited renewable self-generation options, high reliance on the supply sector for electricity provision can be expected as well as a low decentralisation degree. Moreover, another major difference can be observed; the aggregated model relies heavily on coke, while in the TAM-Industry model, natural gas is the main energy carrier used. This is due to different investment in decarbonisation technologies chosen for the different models. Both models rely on production technologies with carbon capture to achieve emission reductions in th CFT scenarios. However, in the aggregated model, coke based carbon capture technology is chosen while in the TAM-Industry model, a natural gas based carbon capture technology is invested on. Once again, the reason for the different investments is a result of electricity prices. In TAM-Industry, the most prominent actor group, which also has the lower electricity prices, invest on a gas technology that has a higher electricity consumption than the coke base technology. Given that the electricity price for this actor group is lower than the electricity price in the aggregated model, the gas-based technology is a more cost efficient investment.

Another difference observed between the two models is the use of biomass and rooftop PV in TAM. Biomass gasification was introduced in TAM for the production of Hydrogen that can be used to partially substitute natural gas as a way to lower fuel emissions. In TAM-Industry CFT scenario, however, biomass is not used despite the high share of natural gas in the energy mix. An explanation for this difference is that the vast majority of the natural gas used in this scenario corresponds to a production technology that employs carbon capture where natural gas fuel emissions are already significantly reduced. Here, investing in biomass gasification for hydrogen production or buying hydrogen from the supply sector does not result in significant emission reductions that can justify the added costs. Rooftop PV investments were also introduced in the TAM-Industry model. Although small, the full potential provided to each actor group is invested on for all TAM scenarios each scenario.

Lastly, the TAM-Industry model shows smoother transitions in the fuel mix among milestone years as cost-efficient investments take place when deemed appropriate for each actor group rather than all at once as it happens in the aggregated model.

In Figure 4.10, we can see that the actor disaggregation in the TAM-Industry methodology brings new insights. For example, regarding the different actor groups, we can observe that the large basic oxygen steelmakers (LB) increasingly become responsible for most of the energy consumption over the milestone years. This is due to the fact that having the lowest electricity price mark up, they are able to increase their market share, hence decision makers in this actor group will have a large impact in the decarbonisation pathways of the iron and steel industry.

Because of the significantly lower CO_2 emissions generated in the electric arc furnace route, there is an increased trend towards electric arc furnace steelmaking. This production route relies on scrap as the raw material and therefore a production route shift from basic oxygen steelmaking to electric arc steelmaking is limited by the availability of scarp. As all of the actors were allowed to invest in electric arc furnace production, the LB actor group are at an advantage to gain large shares of the available scarp with thanks to their lower electricity prices. As a result, we can expect that the basic oxygen steelmaker producers will in the future attempt to gain marker shares in the electric arc furnace route. In fact, the SB actor group in the CFT scenario only produces steel though the electric arc furnace route.

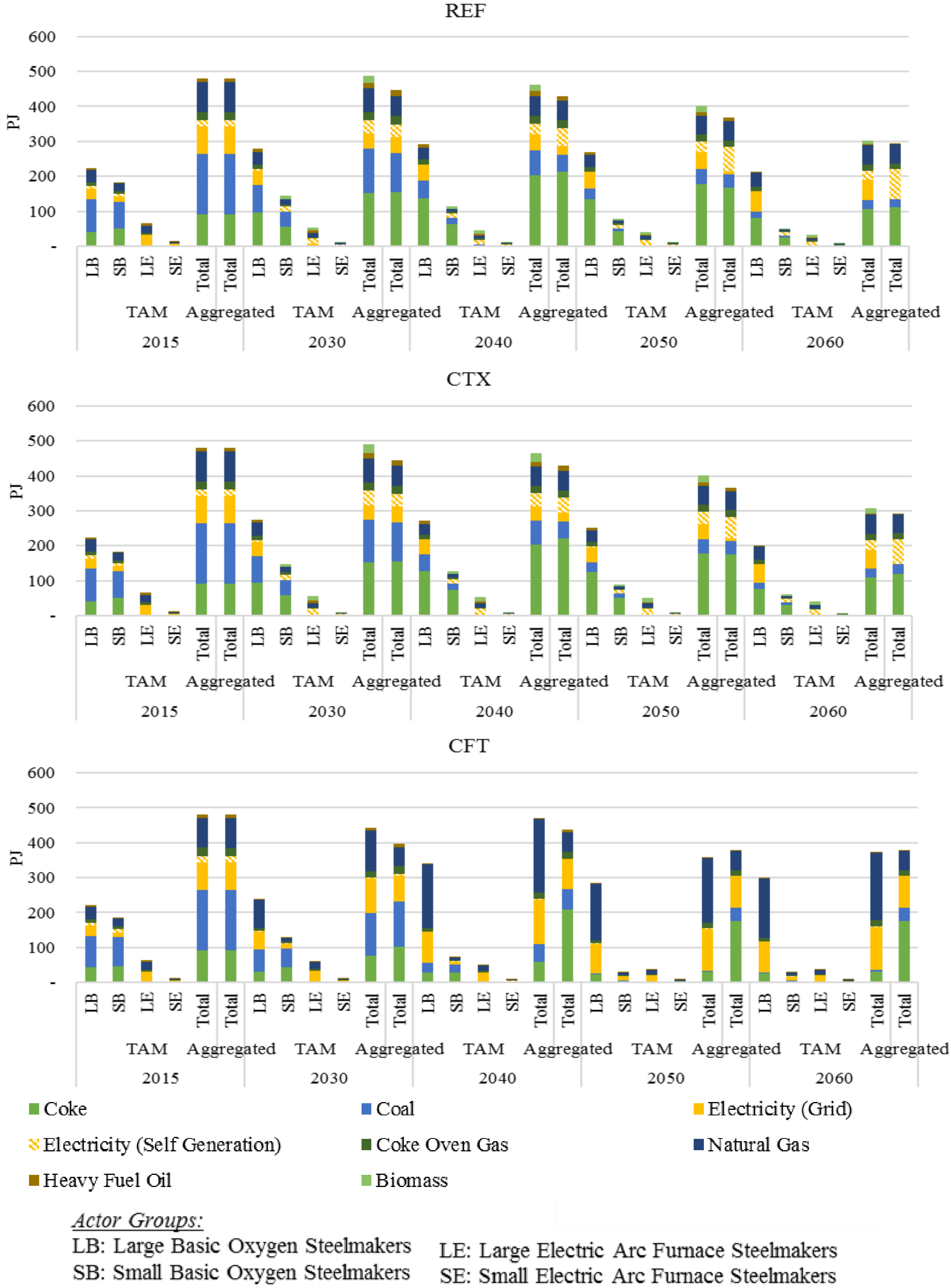


Figure 4.10: Comparison of final energy consumption for Actor Groups in the Iron and Steel Industry by energy carrier for the different scenarios: TAM-Industry vs. aggregated, 2015-2060

Scenario comparison of self-generation in TAM-Industry

A predominant feature observed in Figure 4.11 corresponds to the LB actor group. For LB actors, self-generation is not an attractive investment options as they have the lowest electricity prices. For actors with lower electricity consumption, hence higher electricity prices, there is a perceived attractiveness to invest in self-generation technologies. Full levels of decentralisation can be observed for such actors; SB, LE and SE in the REF and CTX scenarios where carbon tax levels are not high enough to discourage investments in self-generation technologies and despite the additional the carbon taxes associated with it.

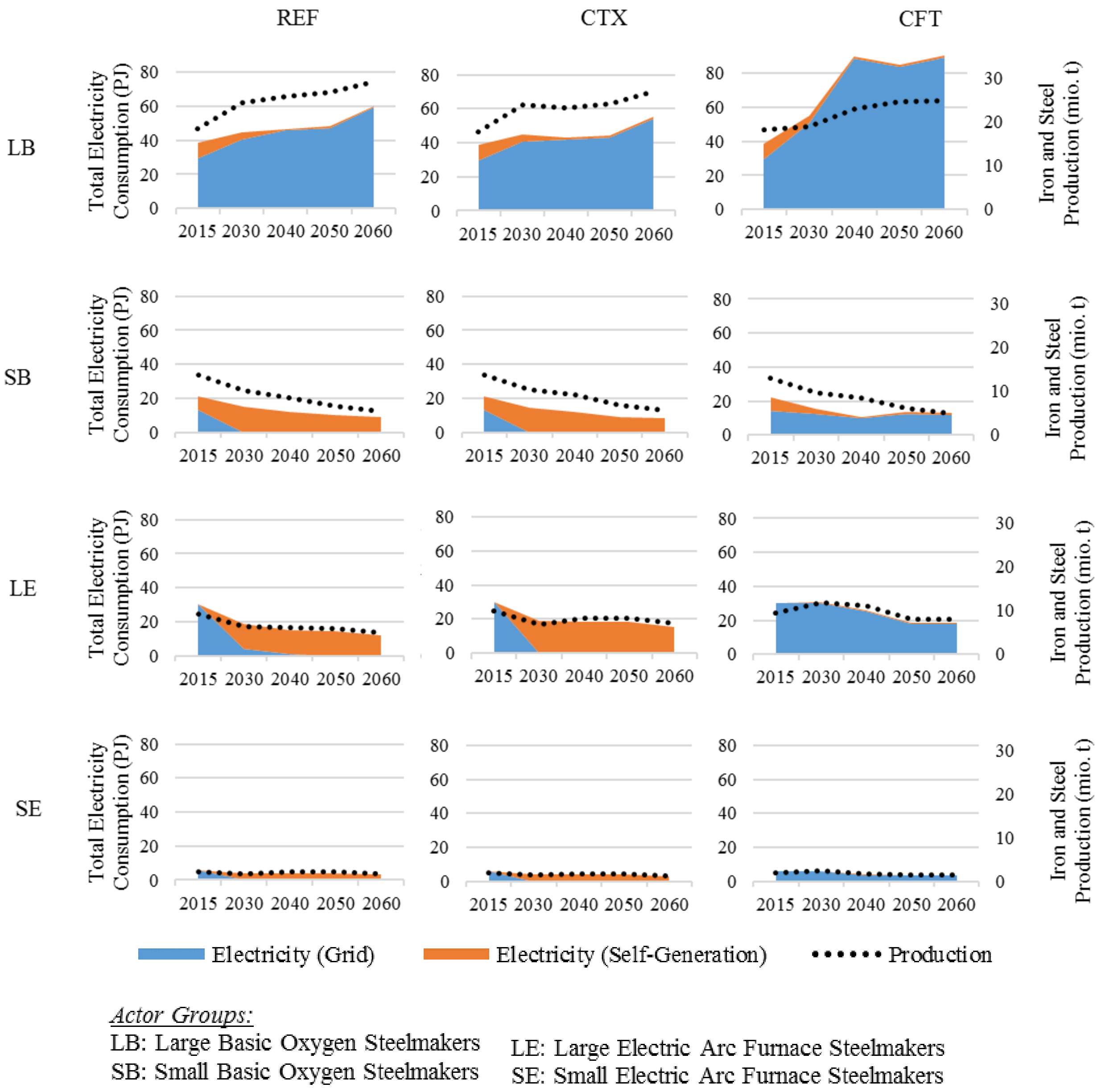


Figure 4.11: Electricity consumption from Supply sector and self-generation by actor group in the Iron and Steel Industry in TAM-Industry, 2015-2060

One long-term result of the different electricity prices for the different actor groups in TAM-Industry is the change in market shares for the different groups. For all scenarios, the large blast oxygen steelmakers (LE) gain a large share of the market. They also in electric arc furnace technology.

Scenario comparison of CO_2 emissions in TAM-Industry

Main polluters are those actors that employ the basic oxygen steel making methods, LB and SB as seen in Figure 4.12. Although they produced about 70% of the iron and steel in 2013, their combined emissions account for almost 95% of the total emissions in this industrial branch. For that reason, there is a clear tendency to switch production routes from BOS to EAF. However, availability scrap is a limiting factor for this transition as mentioned previously. While electric arc furnace producers, LE and SE are not as highly imparted by the carbon tax due to their low emissions, they fail to gain more market share as they are disadvantaged from higher electricity prices in comparison to large basic oxygen steelmakers LE. Here is important to notice that the increased emission levels in 2030 for the REF and CTX scenarios are due to the increased levels of self-generations, which result in increased emissions.

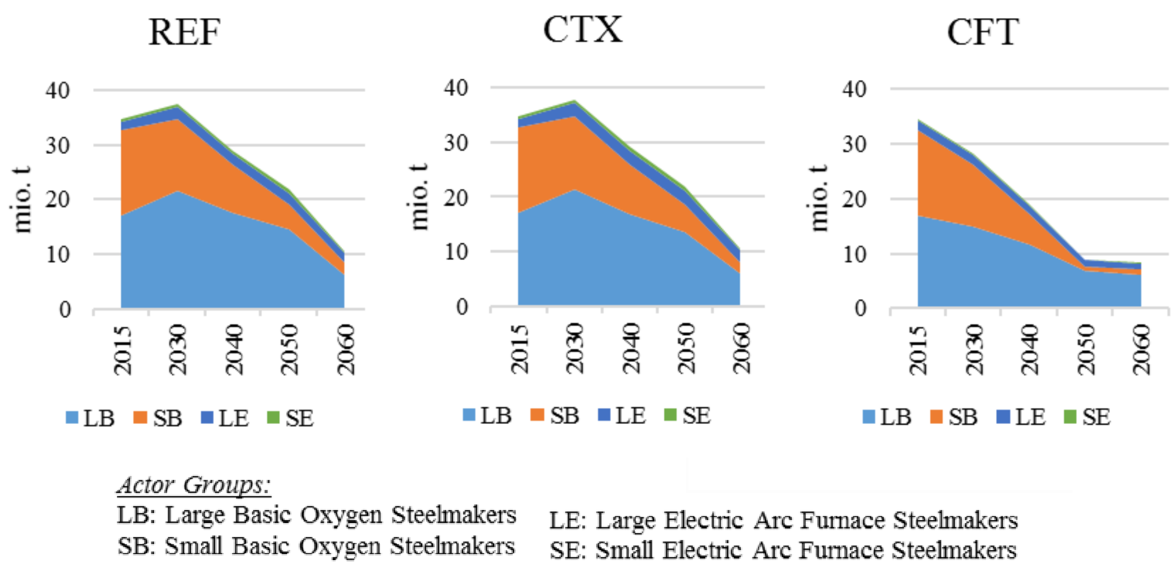


Figure 4.12: CO_2 Emissions by Actor Group in the Iron and Steel Industry for the different scenarios in TAM-Industry, 2015-2060.

TAM_Industry results for the cement and glass industries

Unlike the iron and steel industry, the actors in the cement industry showed a larger sensitivity to carbon taxes. In the CTX scenario, carbon capture technologies are deployed as soon as they are available in the market in order to avoid incurring in the added production costs derived from carbon taxes. Besides carbon capture, key measures in this sector include increasing the share of alternative fuels, lowering clinker to cement ratio as well as self-generation from waste heat and rooftop PV. Investments into novel cements, such as Celitement are only made in the CFT scenario. Regarding the impact of carbon taxes in the glass industry, the results are similar to what was observed in the iron and steel industry. The CTX scenario does not lead to significant emission reduction in comparison to the REF scenario. However, the CFT Scenario shows that by 2050, a further 50% of emissions can be reduced in comparison to the 2050 emission levels in the CTX scenario. Thus proving that reaching high levels of decarbonisation will be cost-intensive.

Insights from TAM-Industry

Looking at the whole industrial sector, the carbon tax implemented in the CTX scenario leads to important emission reduction. Implementing a cap on emissions as done in CFT scenario only leads to a further 4% emission reduction. However, when looking at individual branches, decarbonisation will be a very cost-intensive process as shown by the lack of differences between the REF and CTX scenarios. In the CFT scenario, it can be expected that self-generation will be limited to only renewables, thus putting a higher strain on the supply sector to provide large amounts of electricity while also comply with the energy transition targets. Carbon capture technologies are key for the deep decarbonisation of the industrial sector where fuel and process emissions often cannot be avoided due to the nature of the different production routes. The exercise of the actor disaggregation can provide new insides on the decentralisation potential of this sector as the cost effectiveness of investing in self-generation technologies depends on electricity prices.

4.3.2. Households

This section describes the results emanating from TAM-Households. The first sub-section compares the results of TAM-Households to the aggregated model, followed by a scenario comparison within TAM-Households. An assessment of the shares of self-generation in terms of the contribution towards the decentralisation is provided by scenario, followed by a scenario comparison of the CO_2 emissions by households. This section closes with an overview of the insights provided by TAM-Households towards policy recommendations.

Comparison of results in TAM-Households and the aggregated model

An evaluation of the insights derived from the models depending on the methodology employed is presented in this section. The TAM methodology applied to the household sector as described in Section 2.1 and 2.3.1 is compared and analysed. Figure 4.13 compares the differences between TAM-Households and the aggregated model for the carbon tax (CTX) scenario. Both models are run using the same energy price and carbon tax assumptions. Overall, the aggregated model estimates a higher final energy consumption due to the aggregated demands, with an average total consumption higher by 2-5% between 2020-2055, with differences in the types and shares of energy carriers consumed. The majority of shifts in investments comes in the short-term, between 2025 and 2040, since this is when the bulk of the existing capacities come to the end of their lifetimes and the opportunity arises for new investments. The aggregated model relies less on electricity, gas and solar thermal by instead investing in technologies based on biomass, geothermal and district heating. Multi-family homes (MFH) constitute around 70% of all households from 2013-2060 and thereby represent the majority of total consumption for heating and water heating. Given the aggregated demands in the aggregated model – especially the indistinguishable demands of occupants in multi-family homes - the differentiation between the access to and affordability of resources like biomass, solar thermal, district heating and heat pumps is not considered through the implementation of a budget constraint and leads to the main differences in the results produced between the two models.

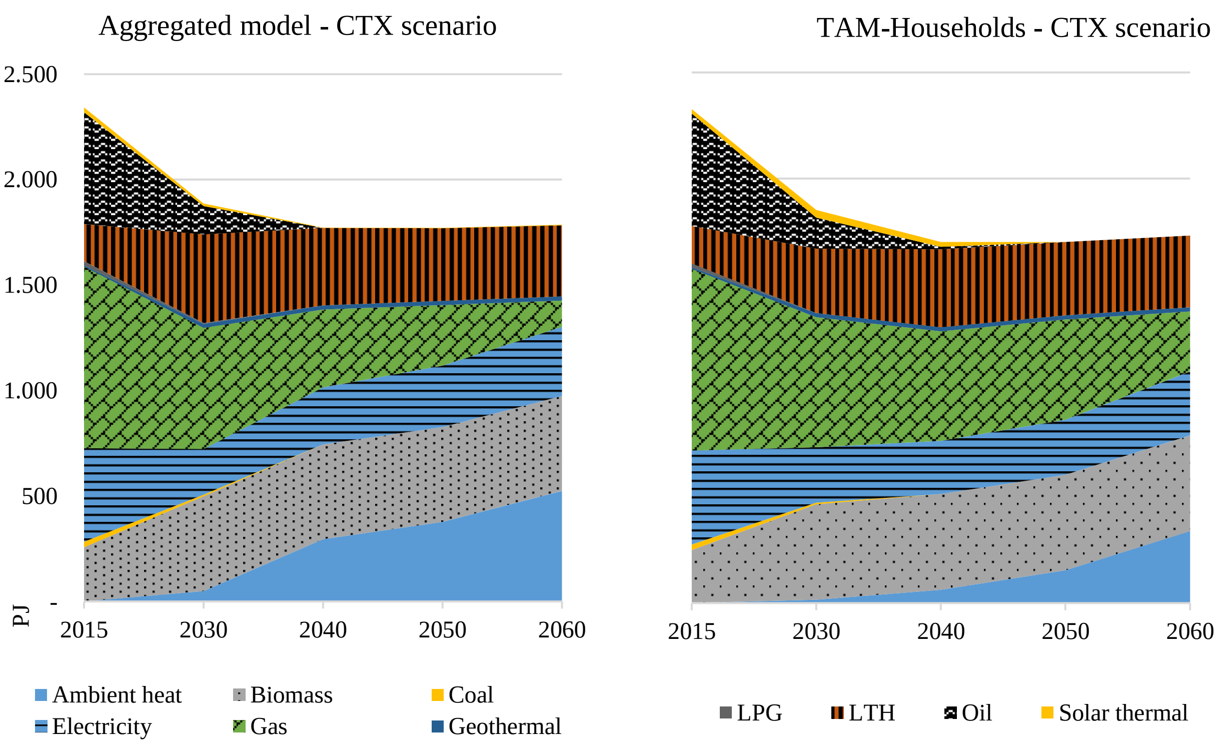


Figure 4.13: Comparison of final energy consumption in the aggregated model (left) and TAM-Households (right) by energy carrier in the CTX scenario, 2015-2060

Heating and water heating consistently account for 84.7-86.7% of total final energy consumption across both models. To better assess these trends, final energy consumption by energy carrier for heating and water heating in multi-family homes for the CTX scenario is compared between TAM-Households and the aggregated model by urbanisation, ownership and energy carrier from 2020-2060 in Figure 4.13. During this period, we observe that the aggregated model estimates a slightly greater overall consumption of energy due to the different assumptions about the required demands for different building types. For example, the aggregated model assumes all multi-family homes are located in the urban area and would have access to district heating, whereas TAM-Households (the disaggregated household sector model) acknowledges that a share of these buildings is located in the rural area where the overall household demands are different. Similarly, ambient heat pumps feature more significantly and much earlier (from 2030) in the aggregated model, thereby more quickly replacing existing and conventional technologies such as district heating and gas.

As the carbon tax increases towards 2050, heat pumps are introduced in TAM-Households and, as can be expected, investments are first made by homeowners. However, since TAM-Households considers the access of different actor groups to specific technologies, it means that different investment patterns emerge that would otherwise be considered in an aggregated group. For example, district heating is restricted to urban areas in TAM-Households, so while the total district heating consumed in both models is similar, TAM-Households considers the building type and ownership (and thereby decision-making power and available budget), thereby offering a view into the cost-optimal investments for different actor groups. Relatedly, solar thermal is also used longer in TAM-Households due to this differentiation. In the long-term this disaggregation has an impact in investment decisions for particular actor groups and therefore on the choice of technologies and associated energy carriers, which will influence the consumption in the long-run if an investment decision is locked-in. For example, once an actor group invests in a particular technology, e.g., biomass, they tend to continue to use this, which is a trend also detected in other countries (Li et al. 2018).

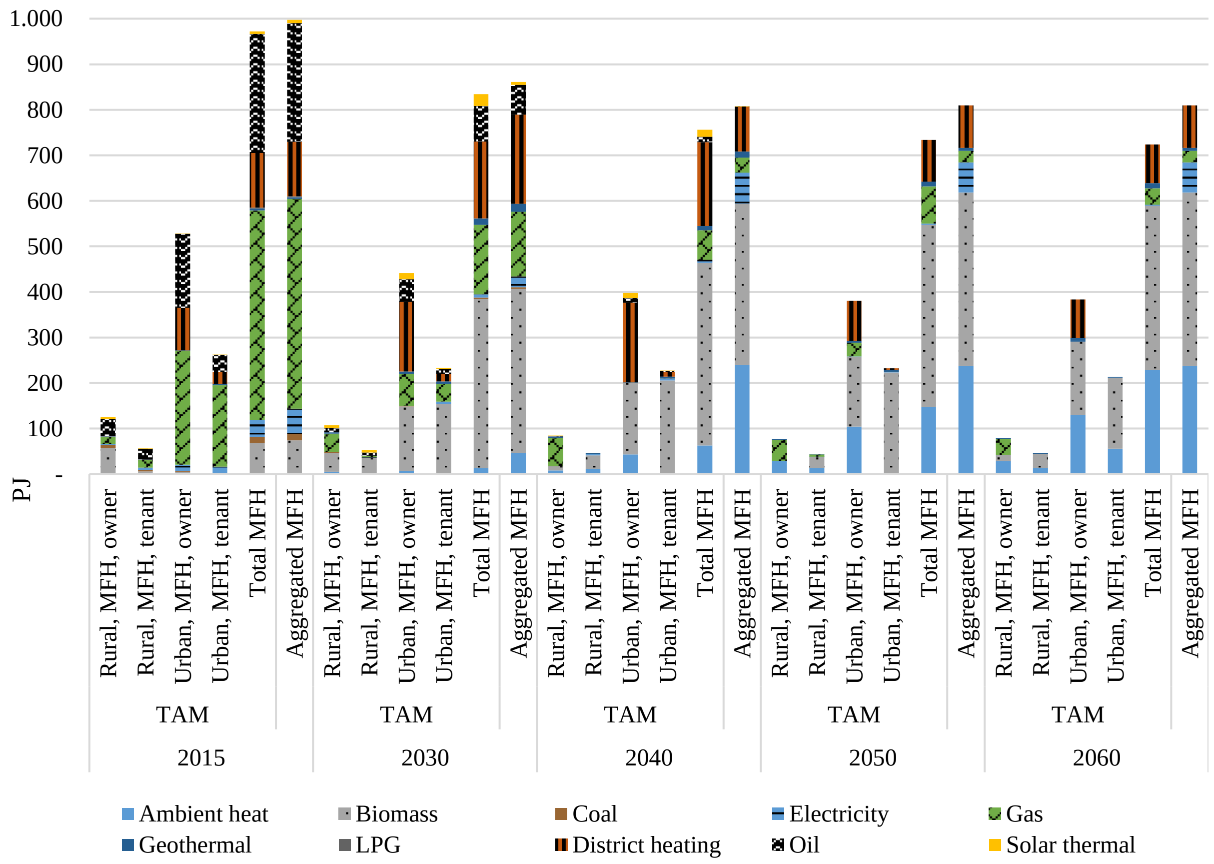


Figure 4.14: Comparison of final energy consumption in the CTX scenario for heating and water heating in multi-family homes (MFH) by urbanisation, ownership and energy carrier for TAM-Households and the aggregated model

Scenario comparison in TAM-households

Across all scenarios, the aggregated model estimates a higher final energy consumption over TAM-Households by between 1-5%, with the majority of new investment decisions occurring in the short to medium term between 2025 and 2040, as shown in Figure 4.15. The final energy consumption in the reference (REF) scenario is almost indistinguishable between the two models from 2045. However, in the short to medium term, the aggregated model favours biomass (20% of total final energy consumption for households in 2035, compared to 10% in TAM-Households) and district heating (22% and 18% in 2035, respectively) whereas TAM-Households reveals higher investments in solar thermal (1.8% in TAM-Households and 0.2% in the aggregated model in 2035) owing to the shift in the attractiveness of this technology over others for urban owners living in MFH and a delay in the investment in biomass technologies due to the immediate access to resources for urban households. Comparing the investment in heat pumps across scenarios shows that this technology plays an increasing role from 2035 particularly in the CFT scenario (representing 15.5% and 231 PJ of the final energy consumption for heating and water heating in 2035), but featuring only minimally in the reference scenario (2.5%). The impact of the higher carbon tax in the CTX scenario acts an appropriate financial disincentive for households to invest into biomass-based heating technologies from as early as 2025 and reaching the full biomass potential by 2035. Comparatively, the other scenarios reach the full biomass potential only by 2045. In contrast, heat pumps represent the cost-optimal solution for heating and water heating in the CFT scenario from 2035, servicing 47.6% and 717 PJ of the heating and water heating demand in 2060 due to the multi-service nature of the technologies (heating and water heating) and the carbon-free consumption to meet these high energy demands. The potential for district heating for the household sector is maximised in all scenarios by 2050 and supplemented with gas and biomass in REF and CTX at 43.3% and 30.5% and 30.6% and 30.7%, respectively, for heating and water heating. The reference scenario will continue to use more gas than in the other scenarios as there are no restrictions on carbon emissions and no financial disincentive to switch to alternative technologies.

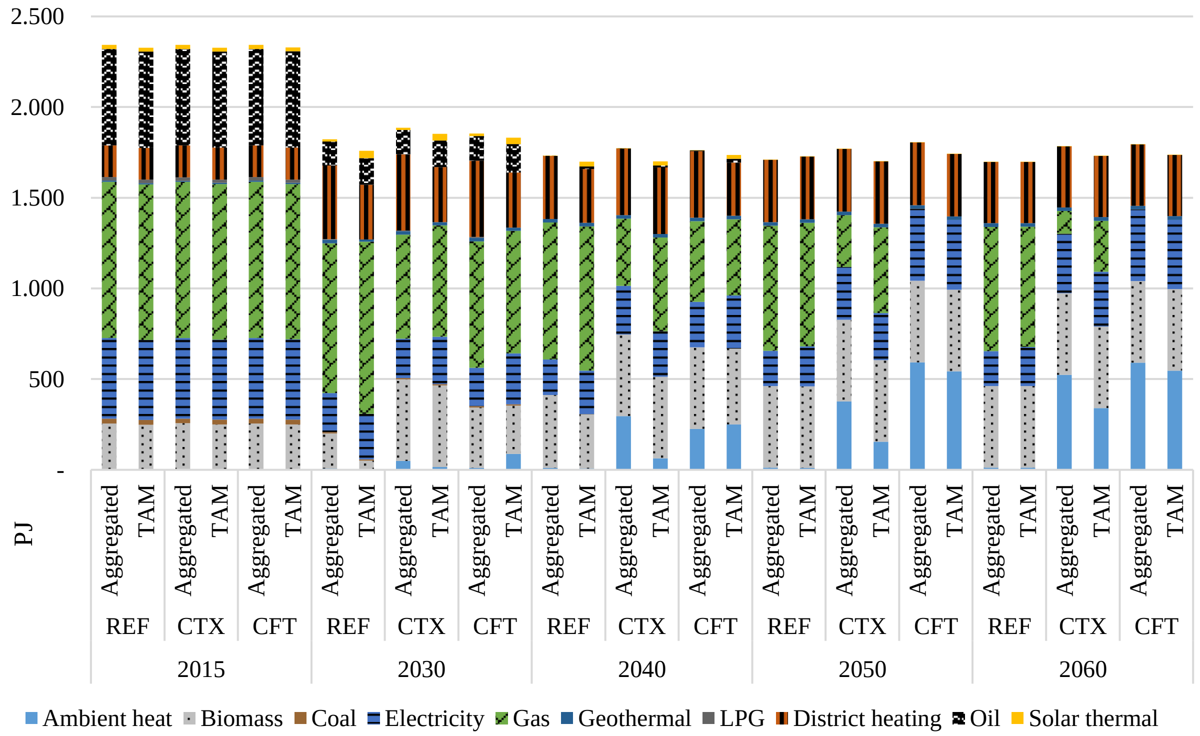


Figure 4.15: Comparison of final energy consumption in TAM-Households and the aggregated model by scenario and energy carrier
Taking a closer look and comparing the cost-optimal technologies for heating and water heating alone across all scenarios in

Figure 4.16 reveals similar trajectories from the base year to 2030 reflecting the phasing out of existing capacities, but the investment trajectories beyond this period differ widely.

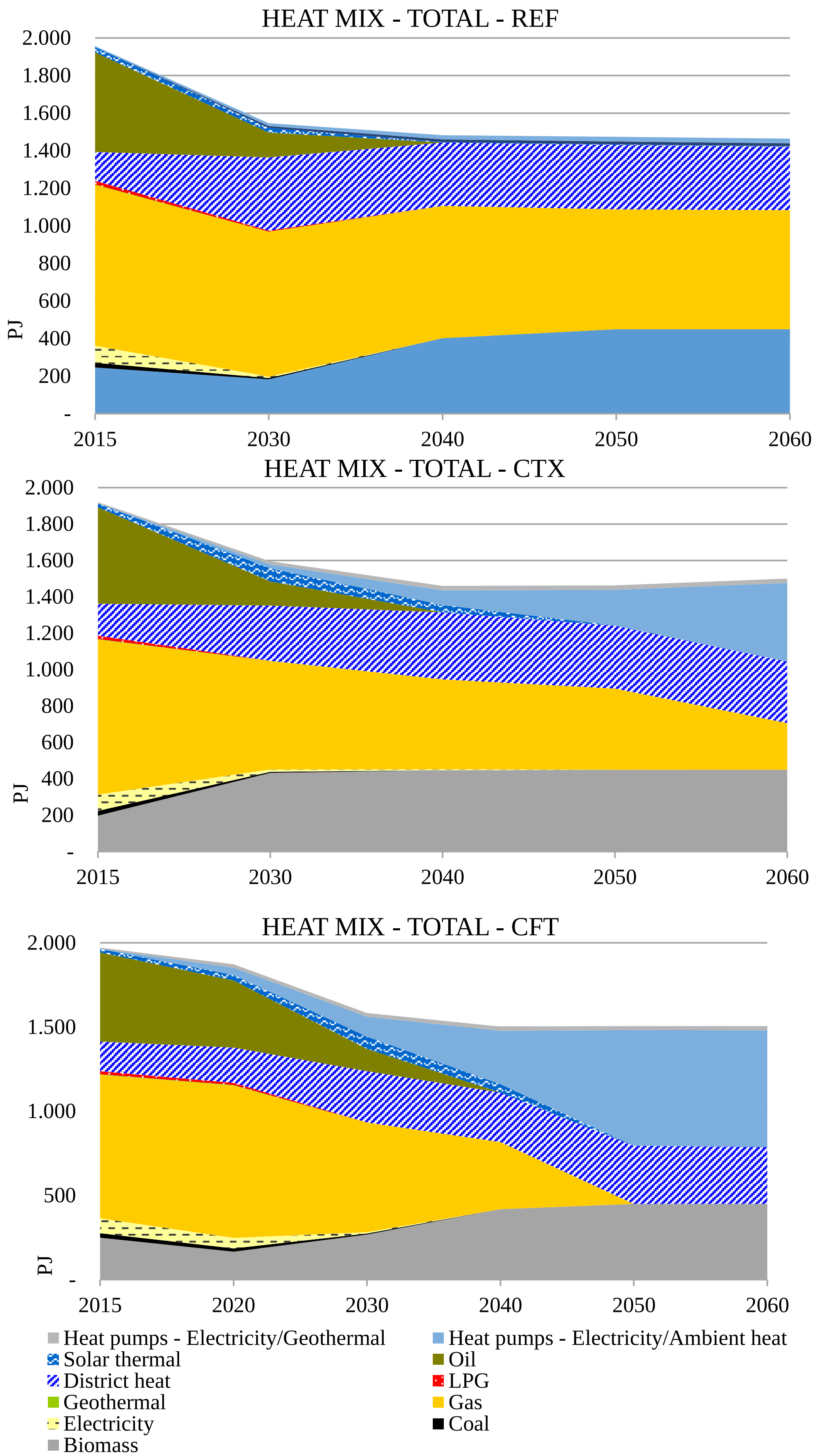


Figure 4.16: Comparison of heating and water heating technologies by scenario

The higher carbon tax in the CTX scenario incentivise investment into carbon-free technologies such as biomass earlier and phasing out dependence on gas. The shift towards the costlier heat pumps is visible in the CTX and CFT scenarios, but are more significant in the CFT scenarios as a full decarbonisation is only possible with investment in these technologies. Without the financial disincentives incurred by the carbon tax, heat pumps remain minimal in the reference scenario and conventional technologies based on gas remain prevalent as described in the previous paragraph.

With the aim of decarbonisation, taking a look at the fuel mix of the final energy consumption by urbanisation, building type and scenario provides insights into the cost-optimal approach towards decarbonising the housing sector in 2050, as shown in Figure 4.17. This reveals that the majority of heat pumps, for example, are in urban areas spread evenly across building types and ownership.

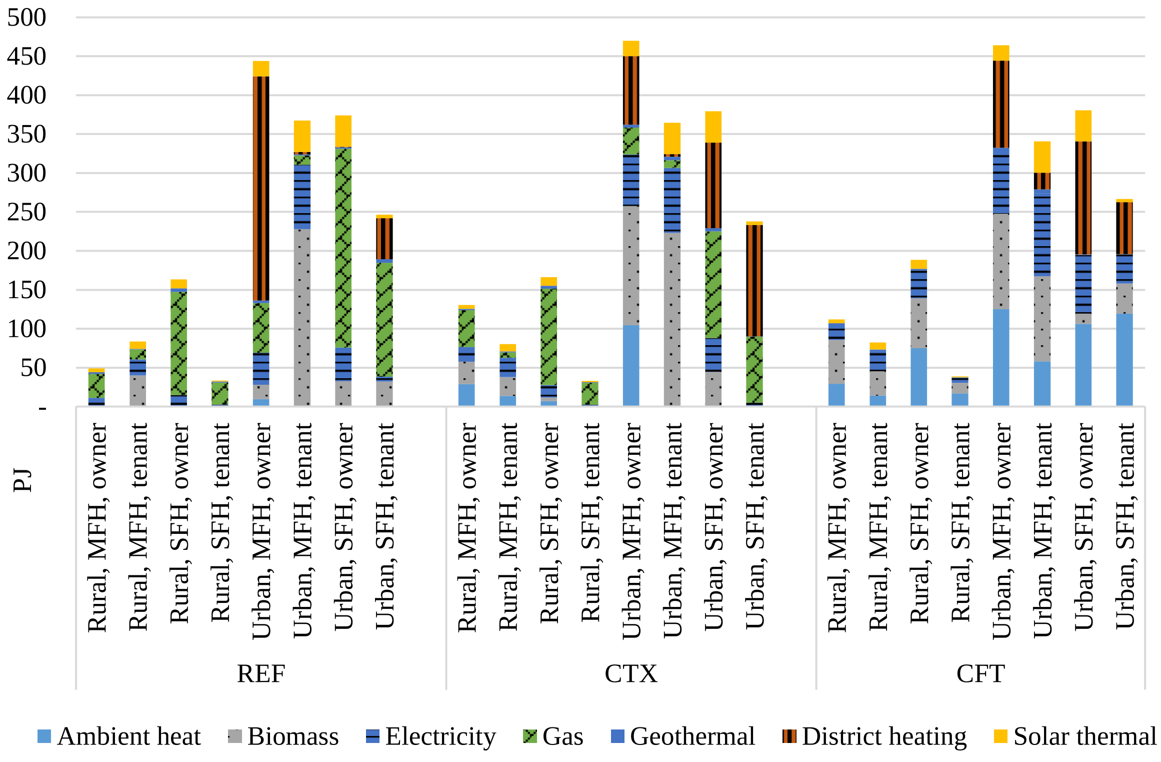


Figure 4.17: Final energy consumption by urbanisation, building type, ownership and scenario, 2050

Scenario comparison of self-generation in TAM-households

The household sector has a maximum rooftop potential for photovoltaic and solar thermal technologies of 42 TWh based on the existing and new buildings. In 2013, the household sector produced 8.6 TWh of electricity through PV, representing 7% of the total electricity consumed, and increasing to the maximum 36.4 TWh in 2060 as illustrated in Figure 4.18. Depending on the electricity consumption in the household sector in each scenario means the share of self-generation in 2060 varies from 60.9%, 43.5%, 48.4% and 34.4% in the REF, CTX and CFT scenarios, respectively. The electricity consumed in the household sector within each scenario is directly related to the costs of consuming decarbonised electricity directly from the supply sector or supplementing energy consumption from other energy sources. Across all scenarios, the same investment patterns into rooftop PV appear with homeowners in both single-family and multi-family homes, followed by the rental sector to maximise the PV rooftop potential to each building type. The CTX scenario represents the exception in 2040 by delaying PV investments for rural tenant MFH and urban tenant SFH to 2045, instead opting to allocate budget towards an increase in investments in the urban tenant MFH sector specifically for heating with biomass due to the growth of the carbon tax.

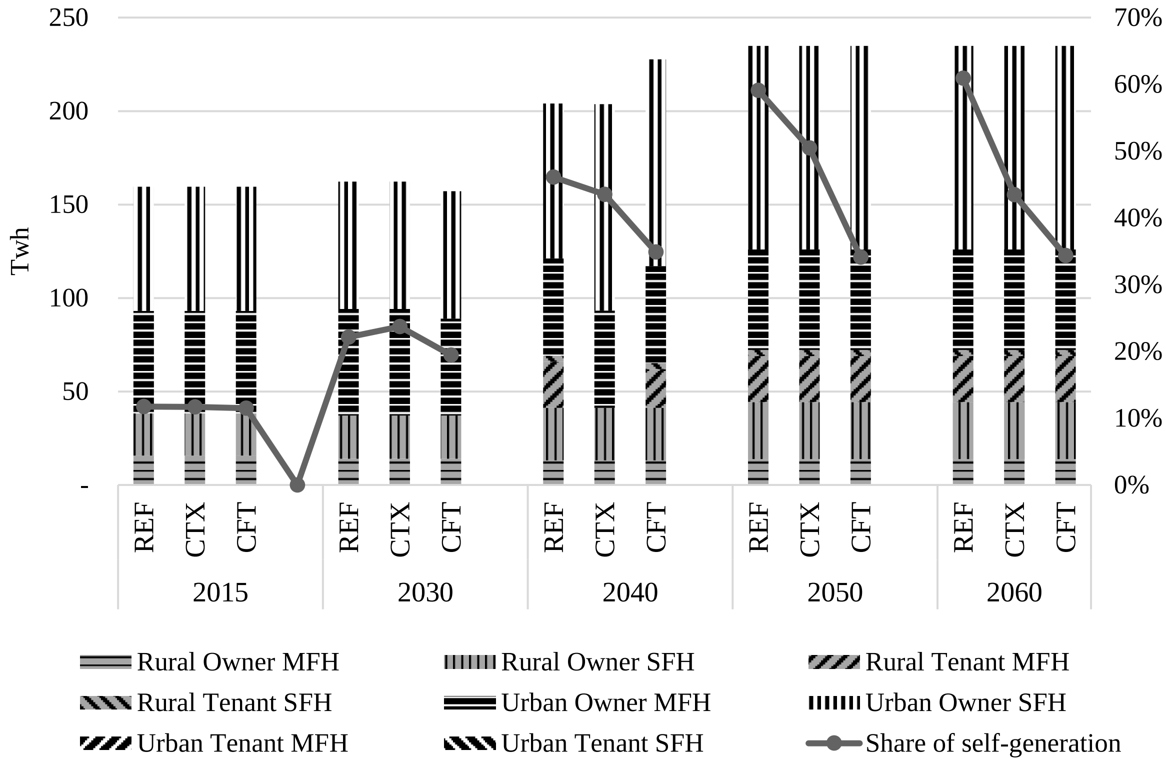


Figure 4.18: Evolution of self-generation in the household sector by building type, ownership and scenario in TAM-Households

Scenario comparison of CO_2 emissions in TAM-households

Reviewing the decarbonisation of the household sector in the different scenarios as shown in Figure 4.19 shows differences in the rates of decarbonisation in the various building types. There is a steady decline in CO_2 emissions in all scenarios from an average of around 85 Mt CO_2 across all scenarios in 2020 to 38 Mt CO_2 and 26 Mt CO_2 in 2050 in the REF, and CTX scenarios, respectively, but we can also observe that the building types revealed as the most difficult to decarbonise are single-family homes in urban and rural areas for both tenants and owners. Referring back to the energy carriers consumed in these specific building types, as illustrated in Figure 4.17, highlights that these building types rely on gas more than other building types as these do not have access to district heating and are less costly than the investment into heat pumps. Furthermore, we can infer which energy carriers will lead to the level of decarbonisation in each specific building type in 2050. Whereas all households feature the use of heat pumps in the CFT scenario (indicating this is a necessary technology for a full decarbonisation), they only feature in the urban owner multi-family and rural multi-family homes in the CTX scenario.

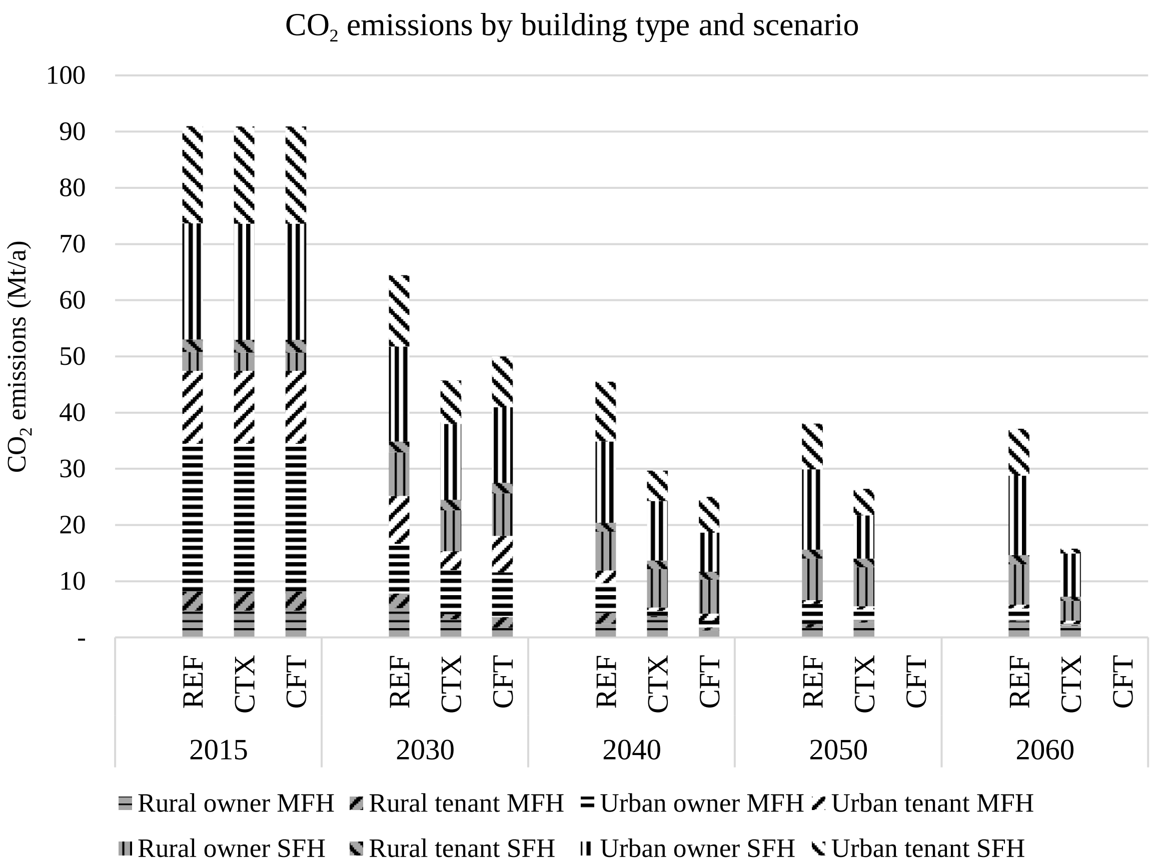


Figure 4.19: Evolution of CO_2 emissions by building type and scenario

Taking a different perspective on the total emissions per urbanisation, building type and scenario in 2050 as shown in Figure 4.20, we see that although urban owner single-family homes account for 19.8% of the population they are responsible for 37.5% and 29% in the REF and CTX scenarios, respectively, due to the heavy reliance on gas (68.4%). Similarly, the other two most carbon-emitting building types, urban tenant single-family homes and rural owner single-family homes account for 2.3% and 0.4% of the population but are responsible for 21.5% and 19.4% of the carbon emissions in the reference scenario in 2050, respectively. These profiles both rely on gas (59.4% and 81%, respectively) to meet most of their heating needs, with the urban profile supplementing with district heating (21.4%). In contrast, the most populous building types, urban tenant and urban owner multi-family homes account for 39.4% and 24.2% of the population and only 1.7% and 9.3% of the total carbon emissions in 2050 in the reference scenario, respectively. Whereas the cost-optimal solution for urban tenant MFH is to shift to biomass use, the urban owner MFH solution is to invest rather in district heating connections, with the differences in outcomes of these two profiles residing in the affordability and decision-making power.

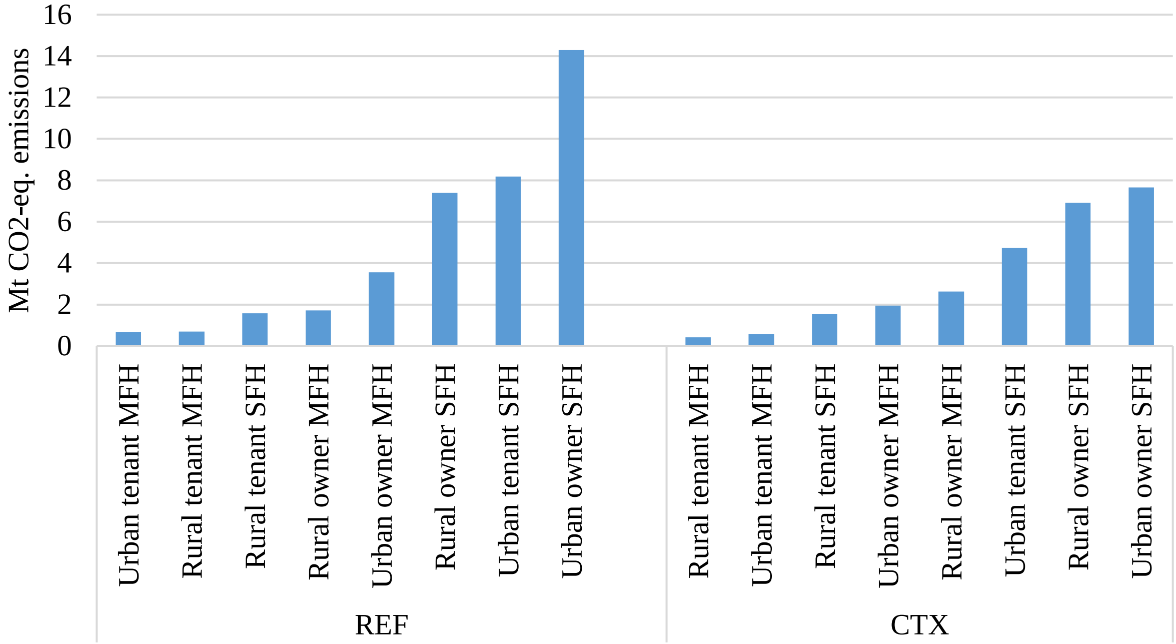


Figure 4.20: CO_2 emissions by scenario and building type, 2050

Insights from TAM-households

Overall, the opportunity to shift the energy carrier type in the household sector is in the short to medium term (2020-2040) when the majority of existing capacities reach the end of their lifetimes and will require new investments. The rental sector is most vulnerable to exclusion from contributing towards the objectives of the energy transition, where these households do not have the decision-making power to influence the types of heating and water heating technologies installed in their homes. As the rental sector continues to account for approximately 49% of the population and 30% of the total emissions in the reference scenario in 2060, this is a sector that will require careful consideration on how to ensure renewable and energy efficient technologies become more significant. Single-family homes produce the greatest emissions overall, accounting for 31.4 Mt CO_2-equivalents and 82.6% of the total emissions in 2050 in the reference and policies tailored to this building type will result in the greatest reduction of emissions. Even with the high carbon tax in the CTX scenario, single-family homes account for 23.8 Mt CO_2-equivalents and 81.8% of the emissions. While lower income households and tenants are more vulnerable to increasing carbon taxes, these profile types would benefit from building-specific taxes, which are reinvested into those building types.

PV technologies have been shown to be a cost-efficient investment in all scenarios and building types, but policies will need to ensure investments in the rental sector are made as this sector does not have the decision-making power for this type of investment. Here, solutions from building management associations may be in a better position to facilitate the types of investments made and will include the rental sector.

4.3.3. Passenger transport

This section describes the results from TAM-Transport. The first sub-section compares the final energy consumption across scenarios, followed by another scenario comparison for the technology mix to meet the transport demand. Furthermore, an assessment of the income groups' long-term choices with regard to the means of transport as well as their final energy consumption is carried out. Finally, the self-generation self-generation in terms of the contribution of public transport providers towards the decentralisation is provided by scenario.

Final energy consumption by energy carrier for each scenario

Figure 4.21 depicts the development of final energy consumption in TAM-Transport (the disaggregated passenger transport sector model) across the scenarios. The comparison of minimum cost solutions for the reference (REF) scenario and CTX scenarios reveals the fact that the passenger transport sector is quite inert against decarbonisation despite very high carbon taxes. The final energy consumption in these scenarios stays dominated by fossil fuels, especially gasoline by private cars, until the end of the modelling horizon with minimum differences across the scenarios. However, the situation is completely different with forced decarbonisation by 2050 in the CFT scenario. In this scenario the passenger transport sector starts to rely more on electricity already from 2030 on to the point that in 2050 the sector consumes only electricity and hydrogen both in public and private passenger transport.

The electricity self-generation in the passenger transport sector starts and grows in all scenarios with a similar pattern with lower amounts in the CFT scenario mainly due to the fact that this scenario requires a capital intensive transition both in public and private transport due to massive fleet electrifications. Therefore, there is little room for self-generation by public transport suppliers because of their budget restrictions.

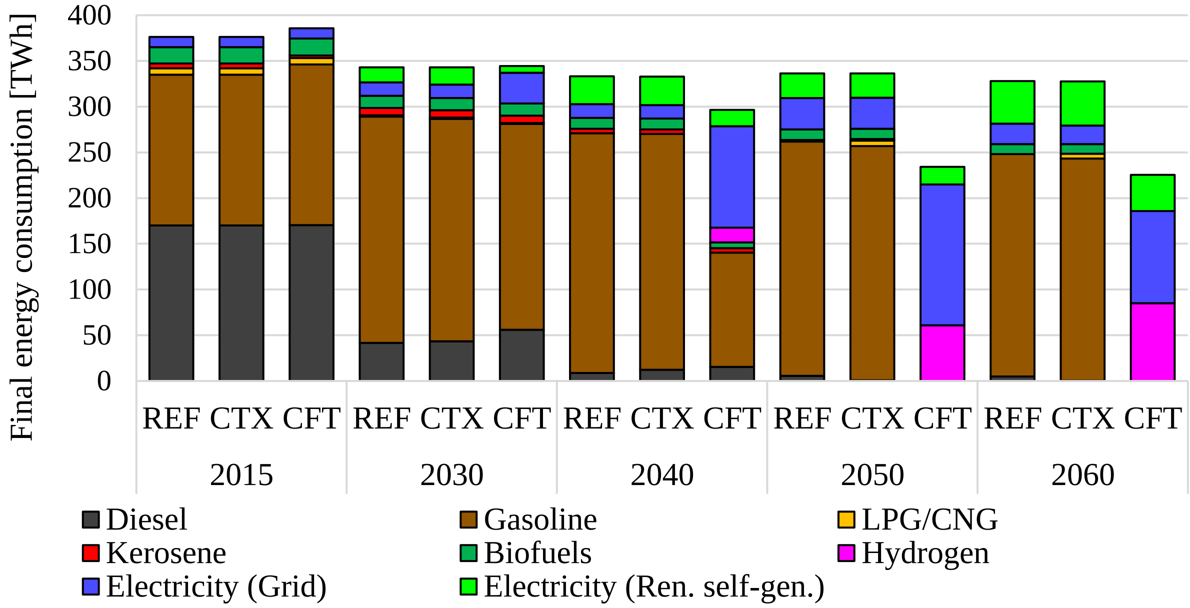


Figure 4.21: Passenger transport final energy consumption across scenarios

Overall Passenger transport technologies for each scenario

Figure 4.22 illustrates the overall technology and mode mix to meet the passenger demand across scenarios. Due to the diesel ban the diesel cars start to phase out gradually until 2040. The mix for the REF and CTX scenarios are quite similar since the decarbonisation in the passenger transport sector is expensive and even the high carbon taxes in the CTX scenario cannot drive the sector towards decarbonisation. This uncover the fact that using only financial instruments is not enough and there needs to be strict regulations for emission mitigation in this sector. Nonetheless, in the CFT scenario where a decarbonisation is forced, the sector starts the transition already in 2030 with uptake of electric cars. In 2050 the hydrogen and electric cars dominate most of the demand fulfilment in the sector. However, the development of hydrogen cars fleet somehow lags behind the electric cars until 2050. From 2050 the hydrogen cars start to have a larger share than the electric cars.

Another aspect that stands out in Figure 4.22 is the modest growth of public transport from 21% in 2015 to 32% in 2060 in all scenarios (the upper part of the bars shown with orange, violet, grey and blue colours) together with the phase-out of national aviation due to its high environmental costs. Therefore, the passenger transport will still be very dependent on the private car fleet even in a strict forced decarbonisation scenario. This is mainly due to the very expensive infrastructure extension for public transport especially the railway system in the shadow of restricted budgets for transport suppliers as well as other decision making aspects by the passengers such as the travel time, since the constraint on the travel time budget is binding for all income groups and in all scenarios. As a result, the public transport sector can play a limited though significant role in the decarbonisation by its high efficiency. However, it will be never enough and a profound decarbonisation in the private car fleet should be sought.

In terms of decentralisation of the demand fulfilment, the private transport sector will stay decentralised due to the dominance of private cars by almost 70%.

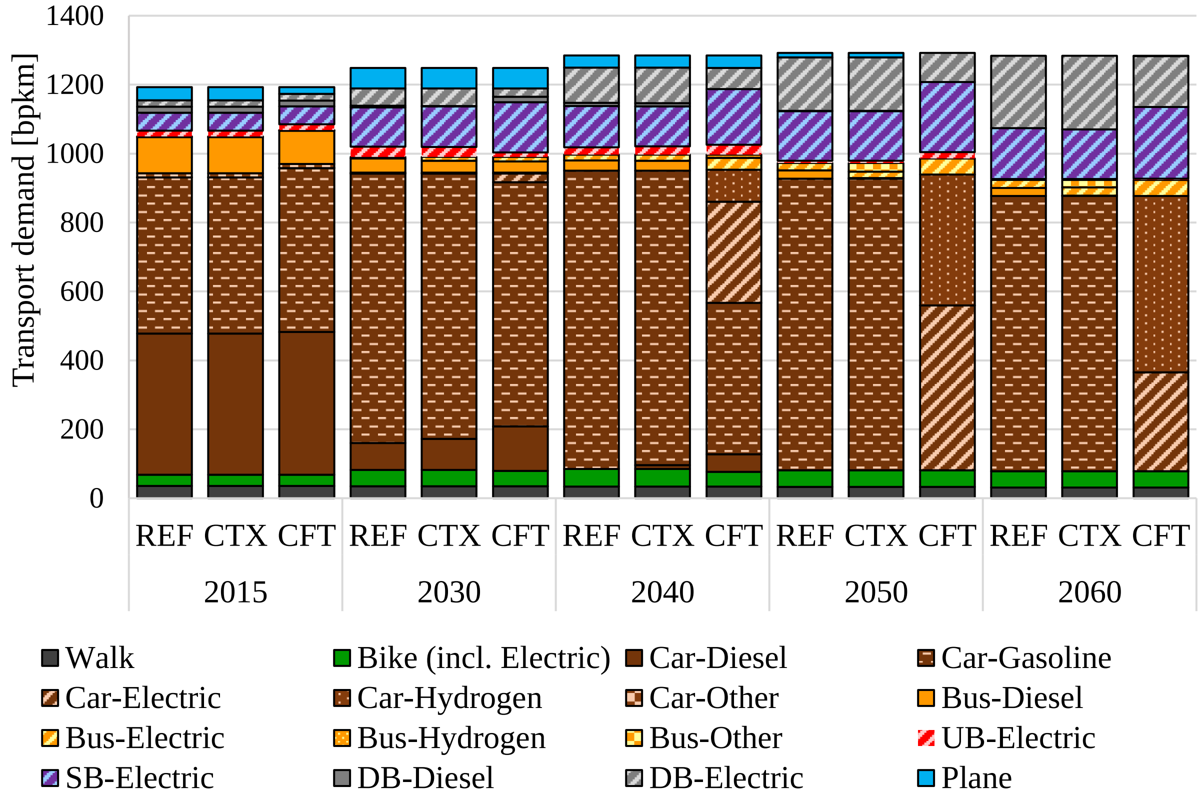


Figure 4.22: Overall technology and mode mix to meet passenger transport demand

Passenger transport technologies per income group for CTX and CFT scenarios

Table 4.2 shows the total transport demand by income group in all scenarios which is given to the TAM-Transport exogenously. This table is presented here to be used for the comparisons of the following figures which show the share of each technology and transport mode in total transport demand of income groups.

Table 4.2: Total transport demand by income groups in all scenarios

Income Group	2015	2030	2040	2050	2060
	[bpkm]				
IG1	42	44	45	46	45
IG2	94	98	101	101	101
IG3	112	117	120	121	120
IG4	148	155	160	160	159
IG5	246	258	265	267	265
IG6	299	313	322	324	322
IG7	252	263	271	273	271
Total	1193	1248	1284	1292	1283

Figure 4.23 shows the technology and mode share in total passenger transport demand per income group in CTX (top) and CFT (bottom) scenarios. As it was explained earlier, the passenger transport sector remains dependent on fossil-fuelled private cars in the CTX scenario. However, the share of private cars in fulfilling the transport demand in each income group is different, reflecting the income classes' ability to afford private car. Therefore, lower income groups own fewer private cars and can afford to use them less than higher income groups to the point that in the first income group most of the transport demand is met by public transport means. This pattern exists in all scenarios as shown here for the CTX and CFT. Nonetheless, the uptake pattern in the CFT scenarios reveals some useful information on how the decarbonising transport technologies are going to be adopted by different income groups.

It can be seen from the lower graph in Figure 4.23 that the first income group to use electric cars in the CFT scenario is the highest income groups (IG7) in 2030. The lower income groups will have to adopt electric or hydrogen fuelled cars though with a much slower pace. This shows the necessity of supporting schemes for lower income groups to make them able to invest in decarbonising private cars. On the other hand, the higher income groups start to adopt electric cars first since the investment cars of the fuel cell cars and the hydrogen generation costs are supposed to make this option more expensive than electric cars in the beginning. However, this does not stay the same over the years and the hydrogen fuelled cars start to dominate the private car fleet from 2060 even by lower income groups. Therefore, this figure shows that the long-term option for the lower income groups will be hydrogen fuelled cars for the part of their demand which is not met by public transport and the electric cars will be used from 2060 on only by higher income groups.

With regards to public transport in the CFT scenario, the least cost solution suggests that the limited capacity of long-distance trains should shift rather towards lower income groups for their long distance trips due to its lower costs in comparison to private cars. However, the higher income groups will need to use long-distance trains less since they can afford to use their private cars for those trips in addition to their medium and short distance trips.

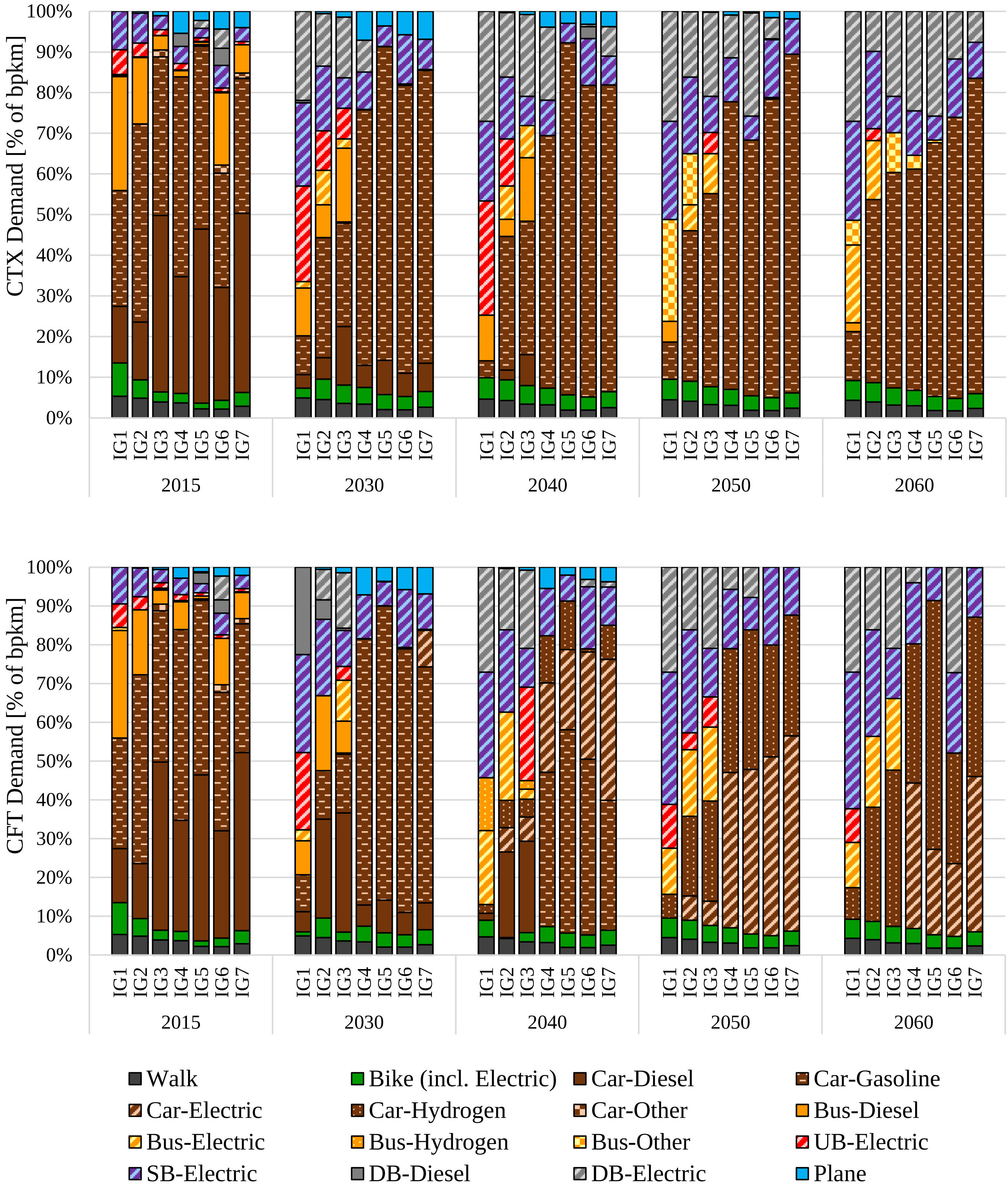


Figure 4.23: Technology and mode share in total passenger transport demand per income group in CTX (top) and CFT (bottom) scenarios

Income groups final energy consumption by energy carriers for CTX and CFT scenarios

Figure 4.24 demonstrates the direct energy consumption in private transport technologies, i.e. private cars and electric bikes, per income group for the CTX (top) and CFT (bottom) scenarios. The higher income groups are predictably larger consumers in both scenarios due to their higher transport demand. However, in the CFT scenario the overall energy consumption decreases gradually for all income groups due to efficiency improvements of the private fleet along with switching to highly efficient hydrogen and electric cars. As it can be seen from Figure 4.24, the drop in energy consumption in absolute terms and also relative to the base year is way more for the higher income groups, especially because the share of private cars in fulfilling their demand is more than public transport in comparison with lower income groups. This reveals the great and easily accessible potential for efficiency improvements and hence emission mitigation by higher income groups because they can afford more capital-expensive decarbonising technologies. Therefore, this should be addressed in policy making to prioritise utilising these low hanging fruits and avoid putting too much pressure on lower income social classes.

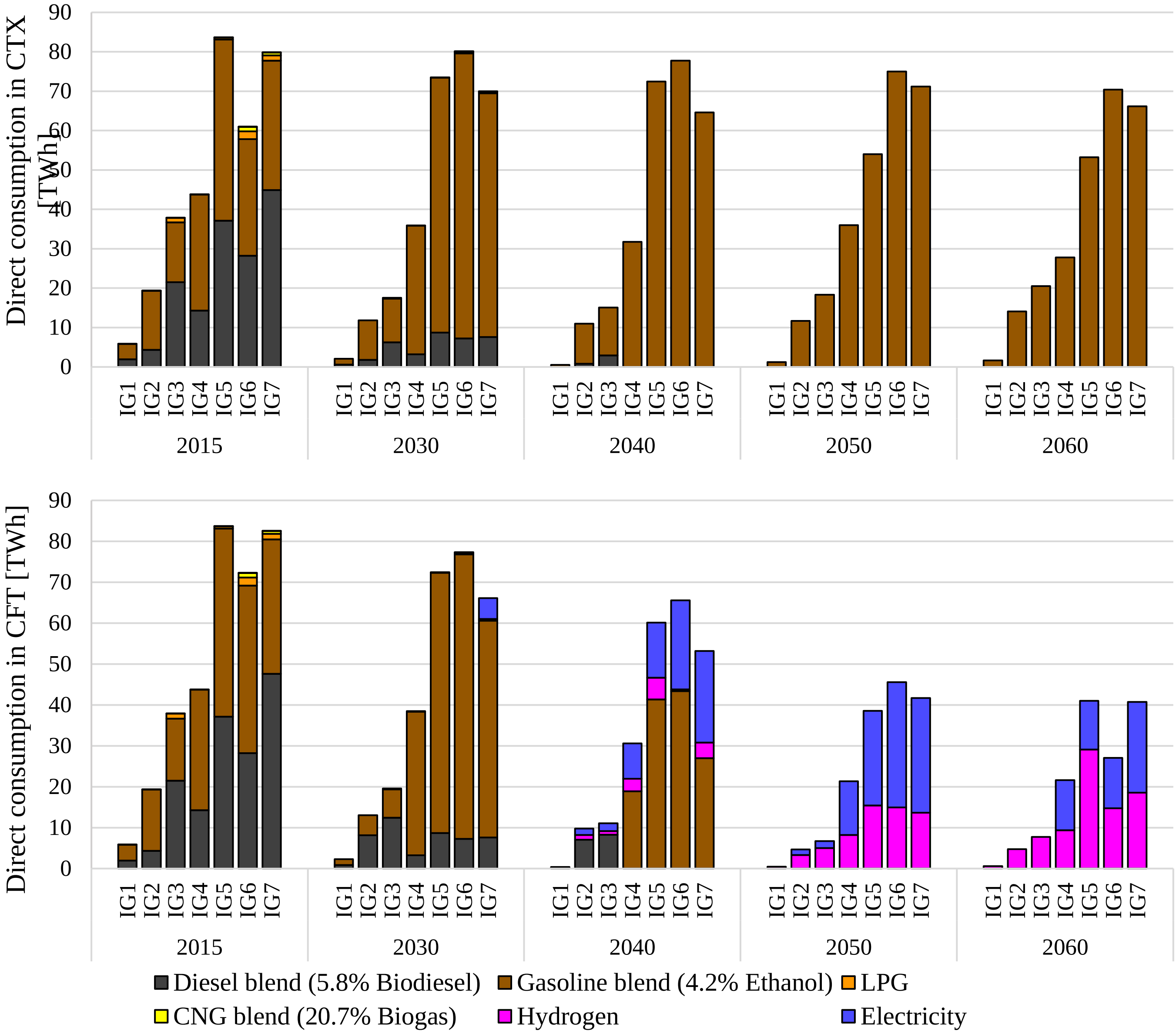


Figure 4.24: Direct energy consumption in private transport technologies per income group in CTX (top) and CFT (bottom) scenarios

Self-generation by public transport provider actors

Figure 4.25 and Table 4.3 respectively show electricity self-generation and its associated capacity in all scenarios and by actors, who provide public transport services. As it is easily noticeable from Figure 4.25 the least system cost solution denotes that all transport providers should investment in onshore wind generation technologies as an interim cost saving measure between 2025 and 2045 to partly generate their electricity demand for electric buses, trams and trains. This happens in all scenario, though on slightly varying levels across scenarios, pointing out to the fact that these investments are rather decoupled from strict environmental policies and are somehow no regret options.

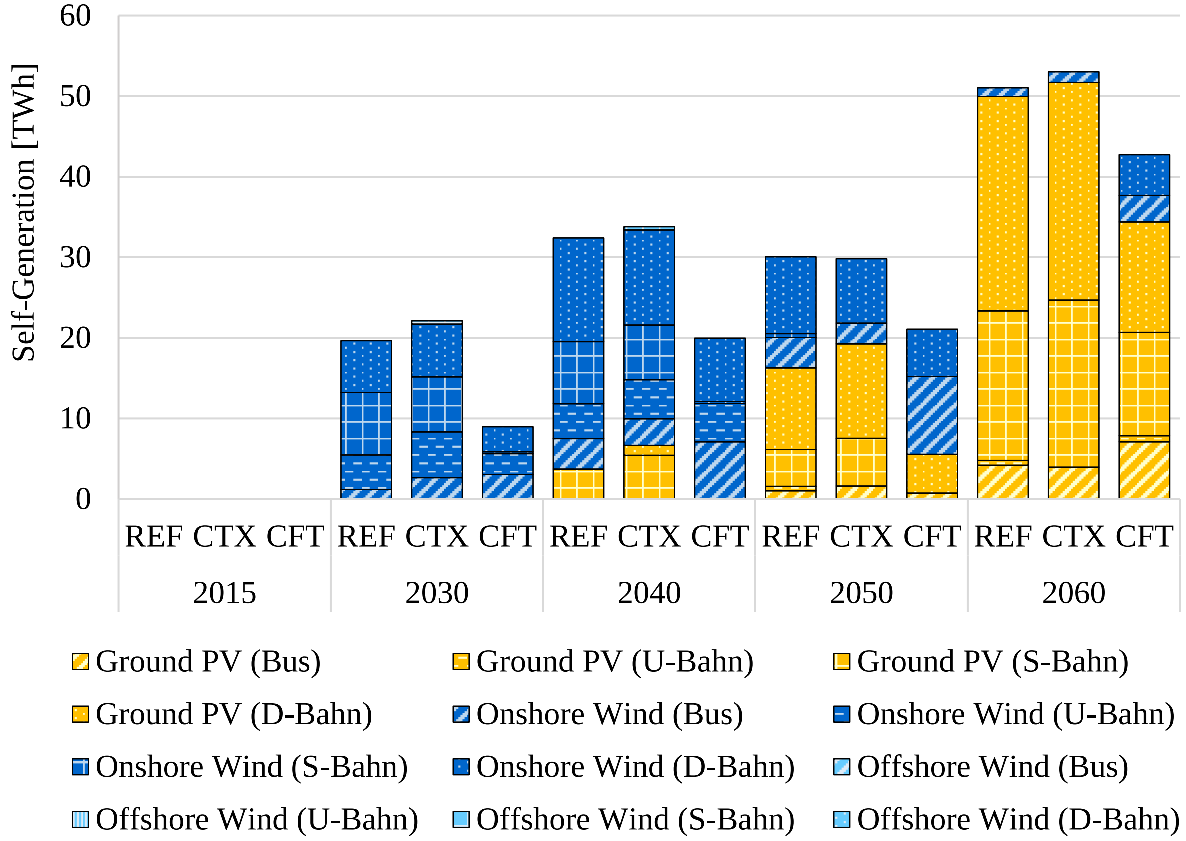


Figure 4.25: Self-generation of the public transport providers by actor and technology

Nonetheless, ground PV starts to steadily grow from 2040 on to the point that it almost entirely dominates the self-generation in the public transport sector by 2060. This is due to the fact that according to current speculations the capital costs of PV technology will continue to decrease longer and further in the future than the onshore wind technology, which eventually might lead to lower levelised costs of ground PV technology than onshore wind in Germany. Therefore, as the ground PV costs decrease below the wind costs, the public transport provider actors switch from onshore wind to ground PV around 2040.

Another aspect of electricity self-generation in public transport sector reveals that offshore wind, despite its higher full load hours, remains unattractive to the actors in this sector especially because these actors do not have any other consideration other than lowering their electricity costs, unlike the actors in the supply sector.

However, there are some limitations to these investments particularly in the CFT scenario as the investing actors have less remaining budget in addition to infrastructure investments to invest in self-generation technologies, especially for S-Bahn providers. This can be seen from Figure 4.22 as well as the lower graph in Figure 4.23, where the role of public transport in meeting the transport demand experiences a gradual increase up to 2060. Therefore, the public transport providers will have to utilise their available budget to invest first in their infrastructure and then invest the remaining budget in self-generation.

Table 4.3: Self-generation capacities of public transport provider actors across scenarios

Technology	Actor	Scenario	2015	2030	2040	2050	2060
				[GW_{el}]			
Ground PV	Bus	REF	-	-	-	1.02	4.21
		CTX	-	-	-	1.59	3.94
		CFT	-	-	-	0.73	7.08
	U-Bahn	REF	-	-	-	0.56	0.60
		CTX	-	-	-	-	-
		CFT	-	-	-	-	0.78
	S-Bahn	REF	-	-	3.73	4.58	18.54
		CTX	-	-	5.43	5.96	20.74
		CFT	-	-	-	-	12.84
	D-Bahn	REF	-	-	-	10.12	26.65
		CTX	-	-	1.24	11.73	27.05
		CFT	-	-	-	4.81	13.71
	Total	REF	-	-	3.73	16.28	50.01
		CTX	-	-	6.67	19.28	51.74
		CFT	-	-	-	5.53	34.41
Onshore Wind	Bus	REF	-	0.58	1.95	1.95	0.53
		CTX	-	1.32	1.64	1.31	0.69
		CFT	-	1.53	3.55	4.95	1.78
	U-Bahn	REF	-	2.16	2.16	-	-
		CTX	-	2.85	2.85	-	-
		CFT	-	2.38	2.38	-	-
	S-Bahn	REF	-	3.86	3.86	0.23	-
		CTX	-	3.41	3.41	-	-
		CFT	-	0.11	0.11	-	-
	D-Bahn	REF	-	3.22	6.43	4.78	-
		CTX	-	3.29	5.90	4.00	-
		CFT	-	1.90	3.98	3.04	2.58
	Total	REF	-	9.82	14.40	6.96	0.53
		CTX	-	10.86	13.79	5.31	0.69
		CFT	-	5.92	10.02	7.99	4.36
Offshore Wind	Bus	REF	-	-	-	-	-
		CTX	-	-	-	-	-
		CFT	-	-	-	-	-
	U-Bahn	REF	-	-	-	-	-
		CTX	-	-	-	-	-
		CFT	-	-	-	-	-
	S-Bahn	REF	-	-	-	-	-
		CTX	-	0.10	0.10	-	-
		CFT	-	-	-	-	-
	D-Bahn	REF	-	-	-	-	-
		CTX	-	-	-	-	-
		CFT	-	-	-	-	-
	Total	REF	-	-	-	-	-
		CTX	-	0.10	0.10	-	-
		CFT	-	-	-	-	-

4.3.4. Supply

This section describes the results from TAM-E-Supply. The first sub-section compares the results of TAM-E-Supply to the aggregated model, followed by a scenario comparison within TAM-E-Supply. An assessment of the role of various actors in different regions and their contribution towards the sector's decarbonisation is provided by scenario. This sections closes with another scenario comparison for electricity exchange between the regions.

Comparison of results in TAM and the aggregated model

- *Electricity generation*

Figure 4.26 illustrates the differences in electricity generation mix between TAM-E-Supply (the disaggregated supply sector model) and the aggregated model in the CTX scenario. The positive (negative) values mean that there is more (less) generation from the specific energy carrier in TAM-E-Supply than in the aggregated model.

The most distinct aspect of this figure is the fact that there is more onshore wind generation in the aggregated model especially from 2040 on, which is compensated by a range of other different energy carriers. This is mainly due to availability of cheaper capital in the TAM-E-Supply version taking into consideration the investors with lower cost of capital than the global cost of capital assumed in common energy system optimisation models. Therefore, Some technologies, which are more capital intensive than onshore wind such as offshore wind, geothermal, ground PV, etc., might become more cost-efficient[17] in some particular conditions once invested in by those actors, who have (limited) access to cheaper capital.

Among those mentioned particular conditions is when the grid costs and losses are taken into consideration. Taking a look at some of the technologies, which replace onshore wind (i.e. untapped hydro, ground PV and geothermal) we realise that these technologies have higher potential and/or availability in the southern region whereas the onshore wind is less potent in this region comparing to others. Thus, the system value of these technologies becomes more visible than onshore wind in the south when we consider grid costs and losses since they can generate locally in the south and hence reduce some costs caused by north to south power transmission link extension. However, this particular condition does not apply to offshore wind. There is more offshore wind in TAM-E-Supply than in the aggregated model since the offshore wind can simply be less expensive if actors with cheaper capital invest in them despite the grid costs and losses due offshore extensions.

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[17] More cost-efficient from a system perspective

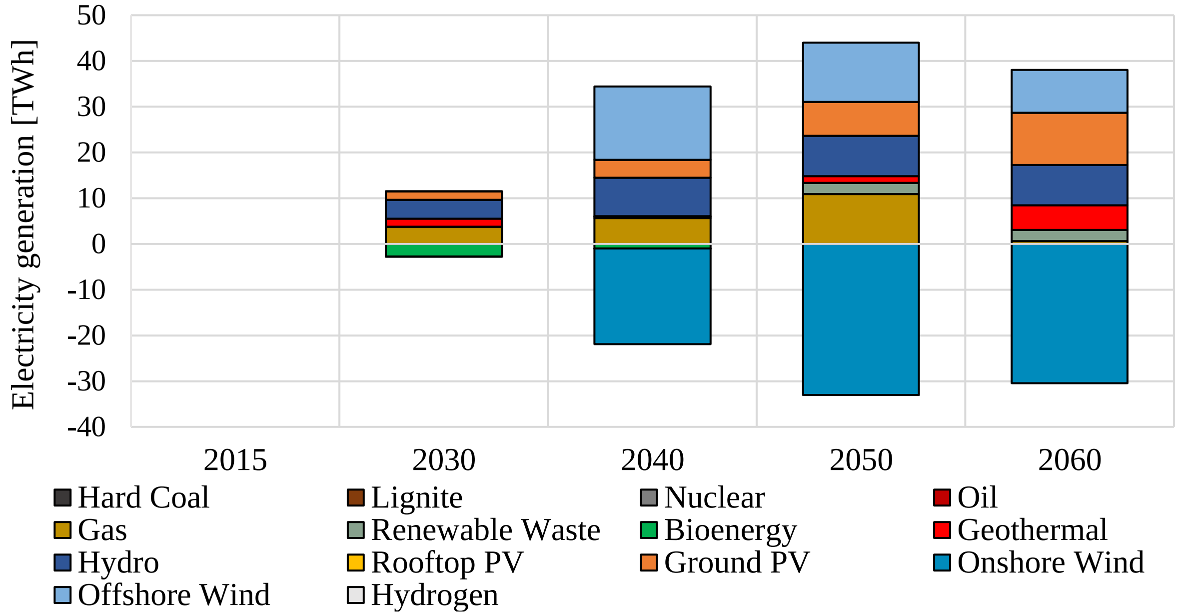

Figure 4.26: Differences in electricity generation mix between TAM-E-Supply and the aggregated model in CTX scenario

Moreover, there is more generation from gas in some of the milestone years in TAM-E-Supply which actually comes from decentral CHP technologies that produce heat in addition to electricity which is then consumed locally. These technologies are also available to citizens and institutional investors with lower cost of capital, since an important driver for these actors to invest in efficient CHP technologies is the creation and retention of value within local economies.

- *Heat generation:*

Figure 4.27 illustrates the differences in heat generation mix between TAM-E-Supply and the aggregated model in the CTX scenario. The positive (negative) values mean that there is more (less) generation from the specific energy carrier in TAM-E-Supply than in the aggregated model.

The most significant difference in the models is that there is more heat generated by heat pumps in the aggregated model, which is replaced mostly by geothermal heat generation in TAM-E-Supply . The reason for this is that on the one hand in the aggregated model the economic potential of producing electricity from renewables and using it in heat pumps to generate heat for district heating is overestimated since the costs and losses of electricity transportation are not considered. In the aggregated model the electricity can be generated anywhere in Germany and used in heat pumps anywhere else. This is of course technically possible but there are more costs associated to it, which makes this option less attractive especially from as system viewpoint. On the other hand, as discussed above, there is more electricity generation from geothermal heat in the south in TAM-E-Supply , which happens in the geothermal CHP technologies. Therefore, some heat could be generated by geothermal resources, increasing the system value of this technology further especially because more geothermal heat could be effectively used from the same source if the electricity generation is coupled with heat generation in a CHP system.

Moreover, there is more heat generation from gas from 2030 on just like electricity generation in Figure 4.26. As mentioned earlier, this conversion happens in local decentral CHP systems that produce both heat and electricity.

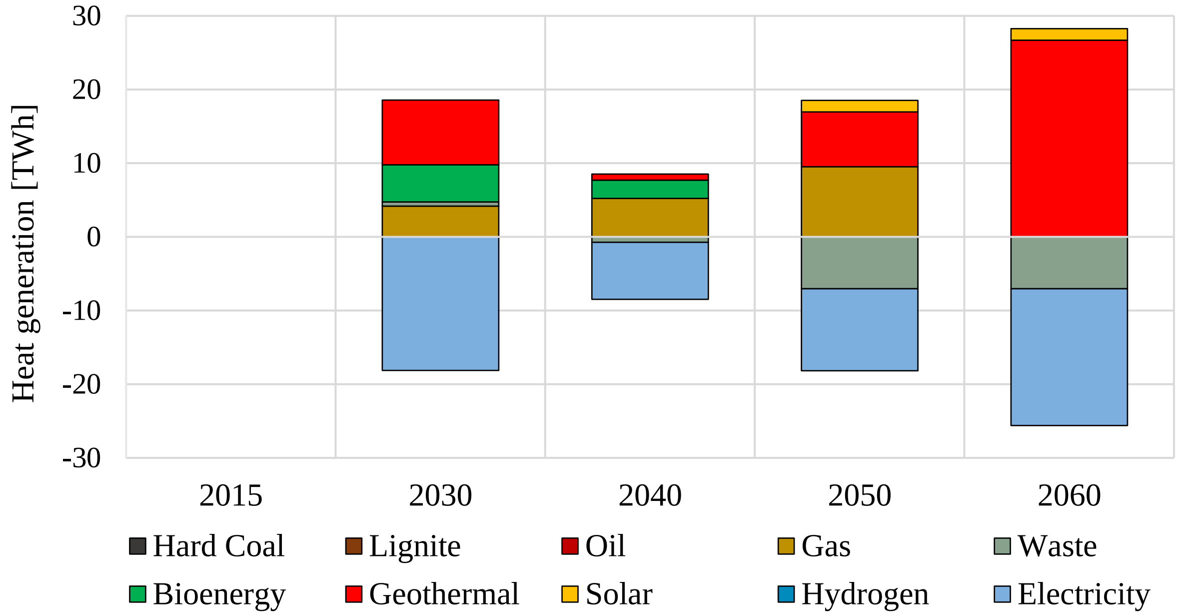

Figure 4.27: Differences in electricity generation mix between TAM-E-Supply and the aggregated model in CTX scenario

Furthermore, heat generation from renewable waste in the aggregated model is more from 2050 on unlike the situation in electricity generation, where electricity generated by renewable waste is more in TAM-E-SUPPLY . The reason is the difference in models‘ choice in these years for the technology f which uses renewable waste. In TAM-E-SUPPLY the technology used is an electricity only technology with relatively high power generation efficiency invested by citizens, whereas in the aggregated model a CHP technology with a much lower power generation efficiency is used at the aggregated model’s discount rate. Therefore, in TAM-E-SUPPLY it is more cost-efficient to allocate the renewable waste to more efficient power generation only with lower discount rate.

Finally, there is slightly more heat generation from solar thermal technology in TAM-E-SUPPLY to compensate for the less heat generated by heat pumps.

Main learnings from actor disaggregation and regional division

- *New investments in electricity generation capacities by actors in regions for each scenario*

Figure 4.28 depicts the overall new investments by actors in regions across scenarios in the form of cumulative installed capacities from 2020 to 2060 for ground PV, onshore wind and offshore wind. Therefore, this figure actually shows how much capacity of the mentioned technologies is required to be installed, including capacity expansions as well as installations replacing retired capacities. This way the overall role of actors in developing towards as well as maintaining the system on the decarbonisation pathways could be observed.

It is evident from the figure that most of the financial potential of citizens, in the form of energy cooperatives, should be utilised for investing in ground PV to varying degrees across regions and scenarios. There will be more ground PV in south almost regardless of the scenario due to higher potential and availability of solar energy. Since there is more electricity demand in the CFT scenario, there is of course more investments on ground PV in this scenario to the point that even some of the available capital from institutional investors is allocated to ground PV in south and west since these two regions have more electricity demand. The rest of available budget from citizens can be used for investments in other technologies (e.g. onshore wind) to varying degrees in different regions.

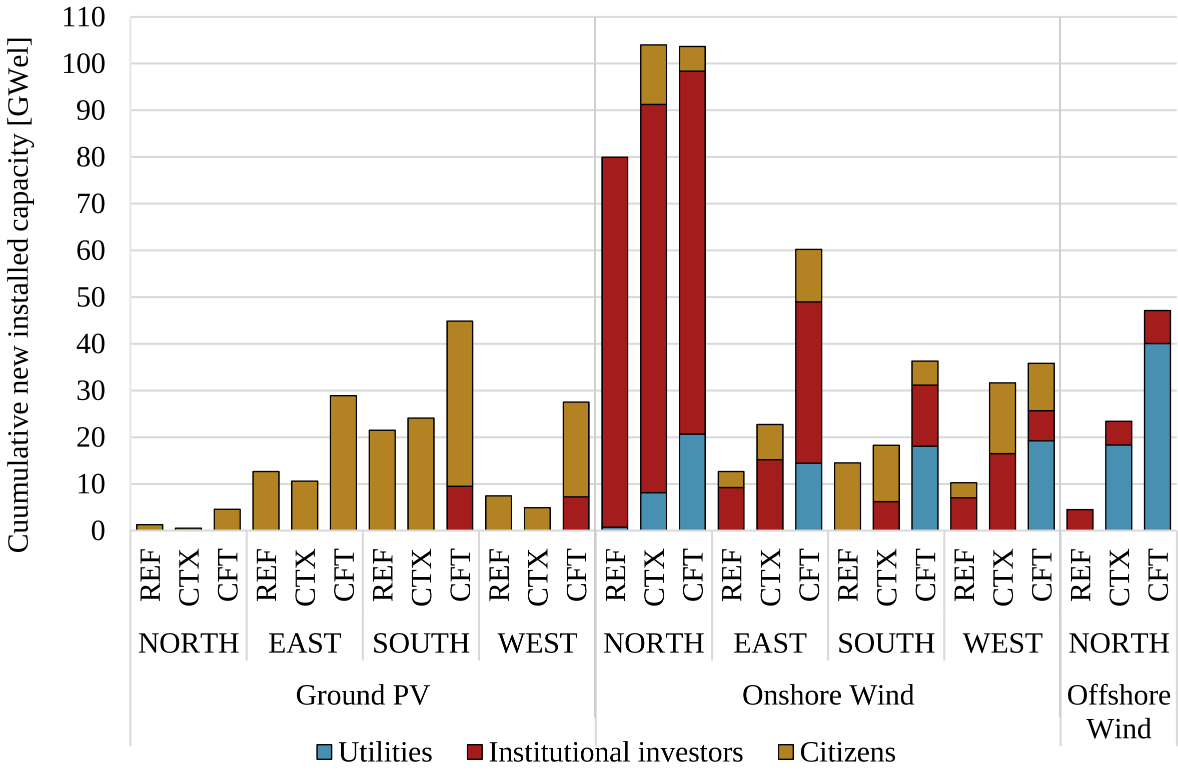

Figure 4.28: Cumulative new installed capacities by actors in regions across scenarios (wind & PV)

Additionally, the institutional investors should focus mostly in onshore wind technologies as they have great value for the electricity system since to some extent they can generate locally requiring less transmission grid extensions. However, the amount of onshore investments varies from region to region and across scenarios. Obviously, onshore wind generation is more available in the north with lower levelised generation costs. Thus, most of the potential in this region should be utilised especially in CTX and CFT scenarios. In other regions onshore wind could be exploited more moderately due to massive investments in the north except for the CFT scenario. In this scenario more onshore wind investments are required in all regions due to very high electricity demand. In this scenario the complementing role of utilities should not be neglected, since not all financial potential of citizens and institutions could be used here. A combination or better said a distribution of tasks among actors regarding different technologies in different regions can be more promising in reducing system costs.

With regards to offshore wind the competition is only between the institutions and utilities. The current least cost solution suggests that the utilities could take up the leading role here especially in the CFT scenario so that the limited financial capacities of the other actors could be used elsewhere. This matches another requirement for offshore investments which, although not modelled, is the fact that offshore wind technology and the associated investments are naturally more sophisticated than other renewable technologies. Hence actors with more knowledge or the „professionals“ in this field could be more efficient despite their higher cost of capital.

Figure 4.29 illustrates the overall new investments by actors in regions across scenarios in the form of cumulative installed capacities from 2020 to 2060 for bioenergy, geothermal energy, run of river and battery storage. What stands out in this figure is the fact that all actors including those with lower cost of capital should still invest in other renewables as well as storages though to a much lower degree comparing wind and PV.

Regarding the citizens we see that they have a dominant role in investments in low voltage local battery storages almost proportional to the regional electricity demand also to ensure the availability of reserved capacity. However, with increasing electricity demand in more decarbonized CTX and CFT scenarios the need for storages becomes more essential and thus institution and utilities should also come into play. In addition to that, the remaining untapped run of river potential in the south is fully utilized in all scenarios by citizens with lowest cost of capital.

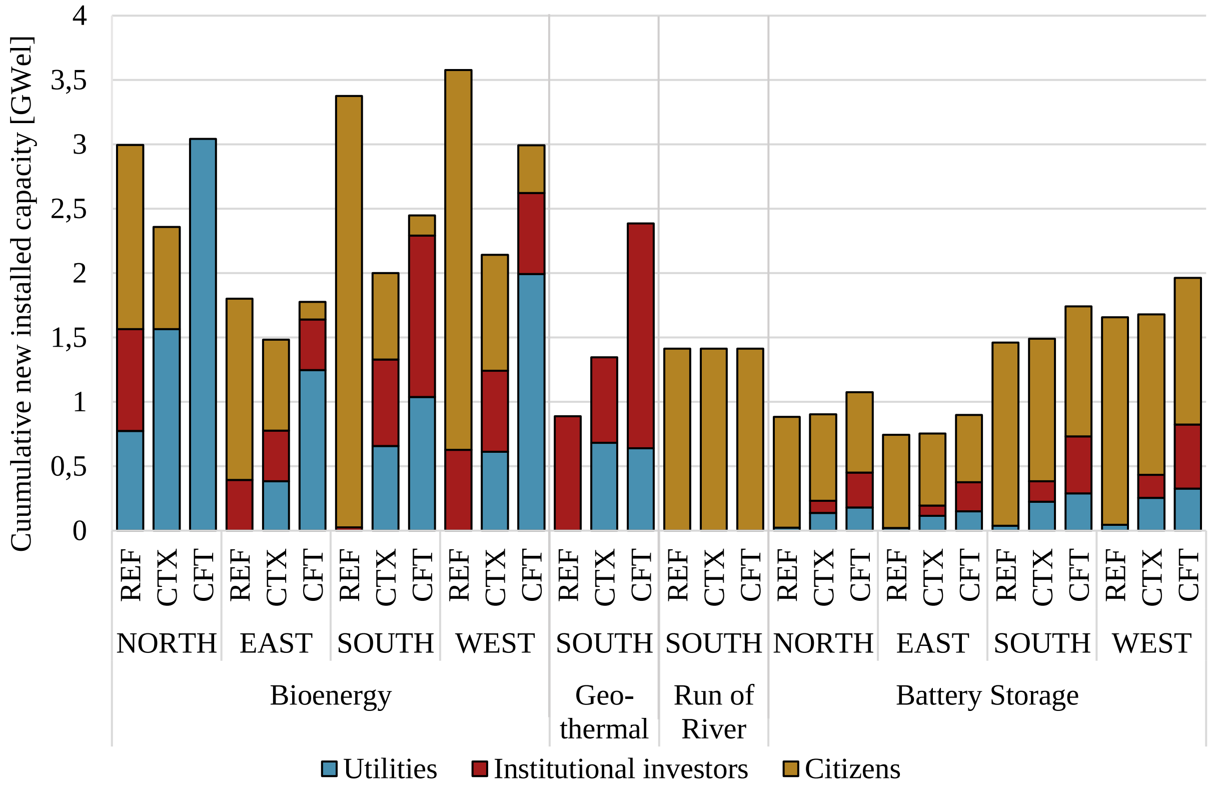

Figure 4.29: Cumulative new installed capacities by actors in regions across scenarios (others)

We can also see in Figure 4.29 that the geothermal electricity generation in CHP technologies in the south should be realised mostly by institutional investors. As the electricity demand grows across scenarios, the utilities should also play a complementing role here.

With respect to bioenergy, we see a varying combination of actors' investment in regions and scenarios. The difference in the regional investments is of course due to differently available regional potential. Nonetheless, the variations in actors' role across scenarios come from the fact that the use of actors' financial potential is configured differently in the scenarios with respect to other technologies especially wind and PV and to a lower degree geothermal, run of river and battery storages. Therefore, the ultimate remaining capacity varies and that is why there are differences in actors' utilisation with regard to bioenergy. Due to the fact that most of the biomass potential is used in the household and industrial sector and the little remaining amount in the supply sector is partly utilized to generate hydrogen, there is really not so much bioenergy left for electricity and heat generation (only little amounts from landfill and sewage gas). Therefore, the use of bioenergy in the setting of the current convergence is not prior to the supply sector and actors are mainly used to exploit other options.

Figure 4.30 shows the overall new investments by actors in regions across scenarios in the form of cumulative installed capacities from 2020 to 2060 for gas and oil which is mostly meant for the reserve capacity. The most important feature of this figure is the fact that the reserve capacity will mostly rely on gas technology and should be realized mostly by utilities. However, there are small investments from institutions and very little from citizens (for local CHP systems).

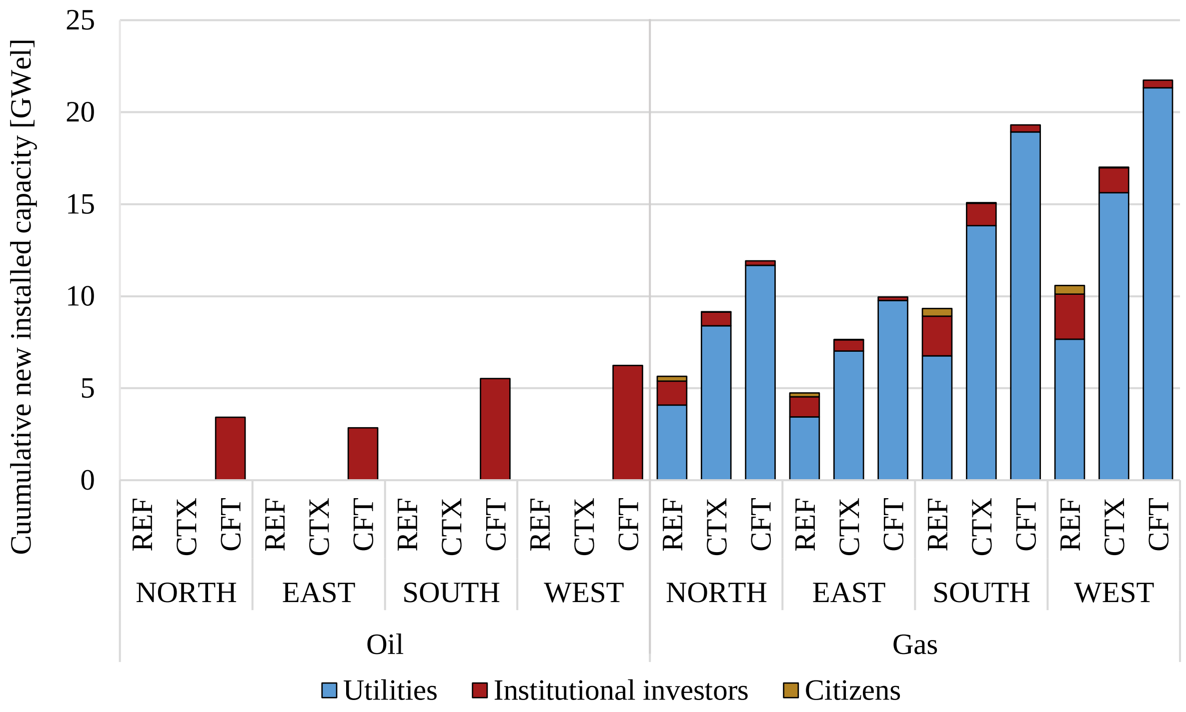

Figure 4.30: Cumulative new installed capacities by actors in regions across scenarios (gas, oil and reserve capacity)

- *New investments in heat generation capacities by actors in regions for each scenario*

Figure 4.31 depicts the overall new investments by actors in regions across scenarios in the form of cumulative installed capacities from 2020 to 2060 for heating technologies including the thermal capacity of CHP technologies. The most important aspect of this figure is the massive investments in solar heating technologies by utilities in the CFT scenario. The reason for this is the high electricity demand in the CFT scenario. Therefore, there is not much room for electric heat pumps and the available potential for heat generation from other resources is limited. As a result there should be large investments in the solar thermal technologies for district heating.

In the other scenarios the district heating is invested in by different actors to different degrees across scenarios. However, the role of citizens in investments in bioenergy technologies especially in south and west is not negligible. On the other great amount of investments in electrical heat pumps are required almost in all scenarios but more in the CTX. A combination of investments by all 3 actor groups especially institutions and utilities are required.

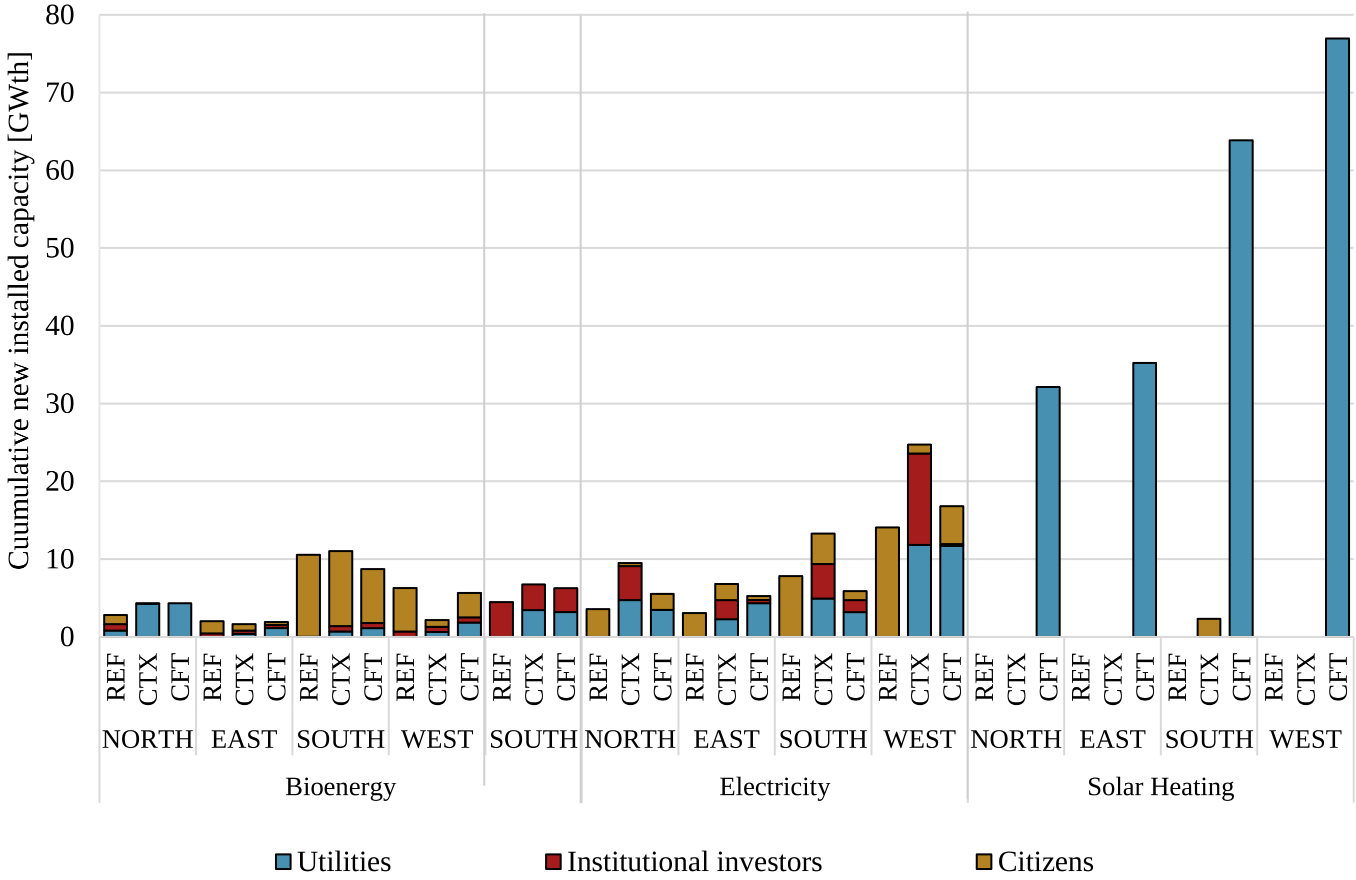

Figure 4.31: Cumulative new installed capacities by actors in regions across scenarios (renewable district heating technologies)

- *Electricity exchange between regions*

Figure 4.32 demonstrates the net power transmission between regions across scenarios. As we can see there is definitely more need for power transmission between regions in decarbonized scenarios especially between 2030 and 2050. However, as the regions develop further on the need for electricity exchange decreases since more local resources are utilized. This figure also shows the extremely significant role of the northern region in the decarbonisation of the German supply sector because of abundant onshore and offshore wind potential in this region. As expected, the southern and western regions are the big importers of electricity due to larger electricity consumption.

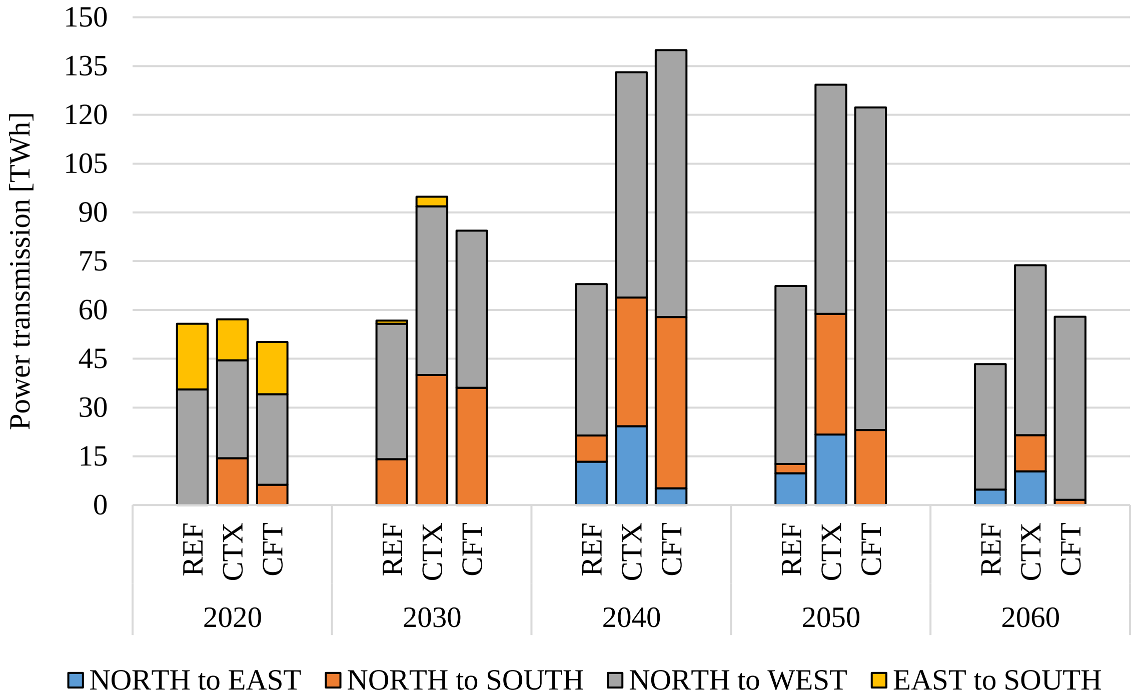

Figure 4.32: Net power transmission between regions across scenarios

4.3.5. Rest

Figure 4.33 illustrates self-generation in the “REST” sector from rooftop PV as well as the degree of decentralisation as the share of self-generation in overall electricity demand across scenarios. As mentioned in section 0, the rest of the energy system is modelled very simplified using demand curves for different scenarios. Therefore, this part of the energy system was constant during coupling iterations and just served to have the approximate overall picture of the total demand for electricity, heat and hydrogen.

With regards to the rooftop PV, it was assumed in the project that only the owner of the building has the possibility whether to invest in rooftop PV or not. Therefore, actors from other sectors were not allowed to invest in the rooftop of the buildings located in other sectors.

As it can be seen from Figure 4.33 the overall PV potential is exhausted quite quickly in all scenarios over the same path, which shows the great importance of the rooftop PV potential as a so-called low hanging fruit for decarbonizing the “REST” sector. The degree of decentralisation goes a similar path with slight differences due to small differences in overall electricity demand across scenarios. However, the ultimate degree of decentralisation in this sector is about 27% for electricity. Therefore, 73% of the electricity demand as well as all other demand commodities (district heat and hydrogen) are assumed to be imported completely from the supply sector.

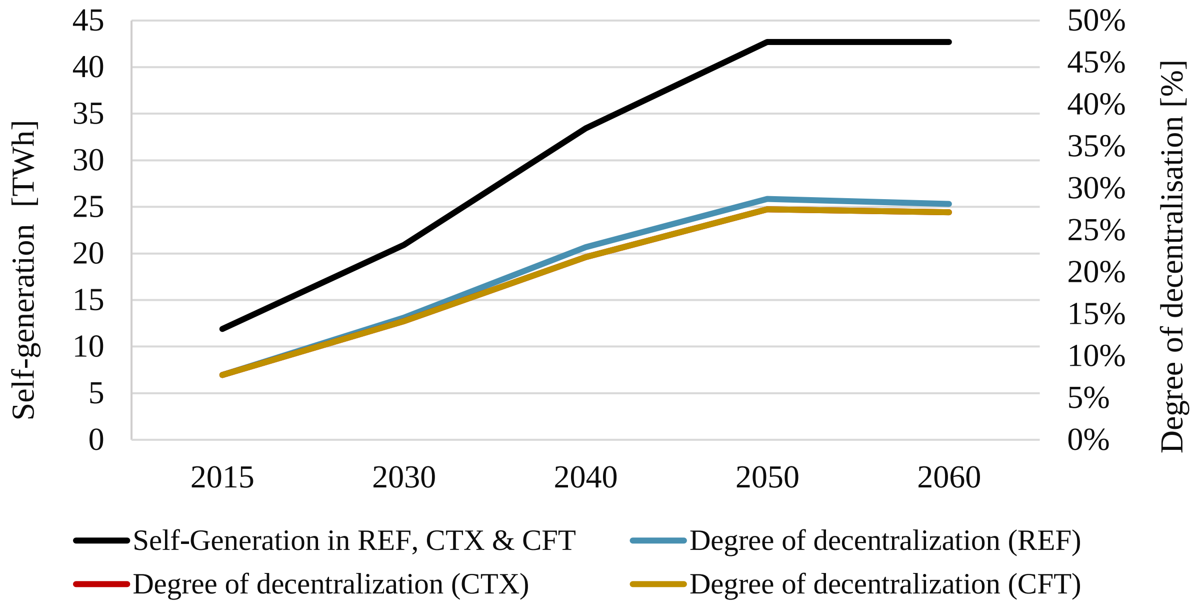

Figure 4.33: Self-generation and degree of decentralisation in the rest of the energy system ("REST")

5. Discussion and conclusion

5.1. Methodology insights

The insights gained through the results show that the methodological extensions to improve the representation of actors in existing technology-rich energy system optimisation models will result in better assessment of supply and demand-side policy needs. The methodological improvements performed within this study with the development of TAM take a step forward to enhance the realism of operation and investment decision making of various actors in separate sectors of the energy system and their interactions. The coupling procedure performed within this study provides the full picture of an integrated energy system with enhanced representation of actors that could help policy-makers to identify applicable innovative solutions which can significantly reduce greenhouse gas (GHG) emissions in an economically and socially sustainable manner relevant to the various actors within the different sectors. Current limitations of the model structure include lack of a high temporal resolution, a finer disaggregation to include further details for modelled sectors as well as more future technology options, for example the industrial sector could include the disaggregation of additional sectors, the household sector could include behavioural parameters and additional building types, the transport sector could include available land as a restricting factor as well as more behavioural parameters such as comfort and the supply sector could include more actors such as the government or a wider available technology portfolio to actors including fuel processing such as hydrogen or biogas generation. Moreover, the detailed disaggregation in this model only applies to actors in the supply, industry, household and transport sectors while the remaining sectors (agriculture, commerce, and freight transport) are simplified. Nonetheless, these limitations do not affect the objective of this study.

The developed model coupling approach proved possible but challenging. The advantages of such an approach over an integrated model are: firstly, the sector models could be extended separately and disaggregated to a finer level of detail with much less complication and conflicts, which facilitated inclusion of sector-specific considerations to achieve deeper insights. Secondly, using separate but coupled sector models provided the ability to incorporate new aspects such as budget constraints taking the costs of consumed energy carriers into account in addition to investment costs which would otherwise not be possible in an integrated model. This separation of analysis enabled insights into the individualised investment and consumption behaviour within the different sectors and underpinned the need for cross-sectoral solutions when aiming for ambitious climate targets as a result of the multilateral interactions among the sectors. Thirdly, the interdependencies of the sectors in terms of energy prices, resource availability and demands became evident through the coupling approach and revealed the impact of the equilibrium between the energy system sectors. Additionally, the interdependencies of the sectors in terms of energy prices, resource availability and demands became evident and revealed the impact of the equilibrium between the energy system sectors. Finally, the coupling procedure reduced the computation time, since the sector models could be run in parallel.

However, the coupling was challenging with respect to convergence, given the high sensitivity of the demand model choices to small changes in the exchanged commodity prices. Another complexity regarding the coupling approach was the fact that the existence of an equilibrium point between the supply and demand sectors does not necessarily guarantee reaching a convergence using normal methods. Therefore, considerable effort was required to keep the iterations towards approaching convergence.

An alternative to the coupling approach would be another iterative method in which all disaggregations and sectoral extensions are incorporated within an integrated model. In order to incorporate the costs of energy carrier consumption by actors, the integrated model could be run using initial guesses for the prices of energy carriers, e.g., electricity, district heat and hydrogen, which are in fact determined endogenously within the solution. After the first iteration is finished, the endogenous prices determined by the solution of the first iteration would replace the initial guesses and the integrated model could be run again for the next iteration. These iterations should be continued until the prices are converged and not changing more than a user-defined threshold across iterations. This method might improve the sector coupling challenges but has its own limitations such as the complexity of the integrated model. The convergence in this method is also not guaranteed, similar to the iterative method used in this study.

Nevertheless, the coupling challenge in this study emphasises where in the energy system the high sensitivity of the optimisation model lies, which would not be visible in an integrated model.

Overall, the methodology adopted for this study to improve the representation of actors in energy system models will facilitate the analysis of policy coordination challenges among related investor and consumer actors increasing consistency of modelling practices and their use in defining low-carbon transition pathways. These insights will be important for developing incentive schemes and market mechanisms fostering technology adoption. The framework is capable of targeting more sensitive investor actors and consumer actors and analysing how non-technological drivers and energy and emission targets can affect investment decisions and maximise cost-effectiveness of the energy system transition.

5.2. Policy insights

Policies are often designed to target specific sectors without consideration for the heterogeneity within that sector. Through the disaggregation of the industry, household, transport and supply sectors, the TAM methodology provided valuable insights for the specific sectors and overall.

Looking at the whole **industrial sector**, the implementation of a uniform carbon tax across industrial branches and actors does lead to important emission reductions that are already relatively close to the technical achievable potential. A further implementation of a carbon cap to bring emission levels to a minimum only leads to a further 4% emission reduction. However, when looking at individual branches, such as the iron and steel industry, decarbonisation will be a very cost-intensive process as shown by the lack of differences between in emissions when implementing a high carbon tax. In a deep decarbonisation scenario, it can be expected that self-generation will be limited to only renewables, which availability is also limited. This will result in a higher strain on the supply sector to provide large amounts of electricity while also comply with the energy transition targets. Market availability of carbon capture technologies are key for the deep decarbonisation of the industrial sector where fuel and process emissions often cannot be avoided due to the nature of the different production routes. The exercise of the actor disaggregation can provide new insights on the decentralisation potential of this sector as the cost-effectiveness of investing in self-generation technologies depends on electricity prices.

Overall, the opportunity to shift the energy carrier type in the **household sector** is in the short to medium term (2020-2040) when the majority of existing capacities reach the end of their lifetimes and will require new investments. While approximately half of all homes are owned, policy guidance can ensure that the rental sector is not overlooked and the potential in this sector is harnessed to its full potential. This is particularly so regarding meaningful investments in building renovations leading to lower heating demand, heating and water heating technologies and exploiting the full rooftop potential for PV and solar thermal technologies. The analysis by building type has shown that specific building types will provide more significant impact if targeted explicitly, for example single-family homes are the greatest emitters of carbon emissions and should be targeted for heating technology retrofits.

Furthermore, carbon taxes alone will not ensure decarbonisation in the household sector due to the heterogeneous nature. Tenants and lower income households will be adversely affected by the tax if the collected funds are not reinvested into those specific households. If higher income households and homeowners benefit by investing in renewable and energy efficient technologies through grants and loans, they will profit disproportionately now and in the future and care should be taken to design policies to target the distribution of funds towards the improvement across the whole building sector. Similarly, PV technologies have been shown to be a cost-efficient investment in all scenarios and building types, but policies will need to ensure investments in the rental sector are made as this sector does not have the decision-making power for this type of investment. Here, solutions from building management associations may be in a better position to facilitate the types of investments made and will include the rental sector.

Moreover, the **passenger transport sector** will still rely on private cars as the dominant mode of transport from short to long travel distances despite almost a 100% growth of the share of public transport in 2060 relative to 2015. This is because on the one hand own private cars are preferred over public transport for many travel purposes due to consumers' decision making rationale, which includes intangible travel costs such as travel time in addition to tangible costs. On the other hand the development of the public transport infrastructure is also very expensive and the public transport providers are pushed towards their budget restrictions. As a result, the passenger transport sector dominated by private cars will remain heterogeneous and creates a significant dependency of the transformation of the sector on the individuals' decision-making for whom even the high carbon taxes are insufficient to alter their consumption behaviour. Thus, the passenger transport sector cannot take much advantage of the efficiency of public transport and proves to be very expensive to decarbonize and very inert against even high carbon taxes and will continue to consume fossil fuels, unless strict measures and legislative supports just like the diesel ban or mandatory emission reductions are employed. In that case, the passenger transport sector starts to go through the desired transition as shown in the carbon-free targets scenario. However, this transition does not happen uniformly across consumers from different income groups. The higher income classes start earlier to adopt decarbonizing technologies, i.e. electric and hydrogen fuel cell cars, and will play a crucial role in the decarbonisation of the private transport sector due to their much higher demand than lower income groups. The lower income groups, however, cannot afford a speedy switch to decarbonizing technologies and will need to rely more on public transport to fulfil their travel demand. Consequently, the maximum possible capacity of the public transport will be used mainly by lower income groups and therefore the higher income groups will be forced to use their own private cars even more than before also for their long distance trips. Regarding the self-generation of electricity by public passenger transport providers, it was seen that the onshore wind technology is the winner among others including ground-mounted PV and offshore wind from 2030 to 2050. However, with PV costs falling below onshore wind costs, the transport suppliers gradually switch to ground-mounted PV technologies around 2040 until it is the dominating technology by 2060.

Finally, in the **supply sector** the role of investing actors across regions in Germany are different in different scenarios. However, there will be massive investments in onshore wind by institutional investors particularly in the north in all scenarios. Since the grid electricity demand in the carbon-free targets scenario is very high especially by the household and passenger transport sectors, there should be more investments in onshore wind in other regions especially in the east again by institutional investors. On the other hand the utilities will have to play the dominant role in investments in offshore wind in the north and in bioenergy throughout Germany with some complementing help from institutional investors and citizens for the latter technology. Moreover, citizens in the form of energy cooperatives should be more focused on the ground-mounted PV in all regions particularly in the south. In addition to ground-PV the citizens should use the rest of their financial potential for investments in the untapped hydro in the south, battery storages and to some extent bioenergy together with utilities and institutional investors. In addition to main decarbonized generation technologies the utilities will have to guarantee the security of supply by their investments in gas reserve capacities. Furthermore, all three actors should invest in renewable district heating generation as well as heat pumps. However, if the strict carbon-free targets are to be met, there is not much room for electricity intensive heat pumps since it would be an additional burden in this scenario due to the already high electricity demand from demand sectors. Therefore, in this scenario massive capacities of solar thermal technology by utilities should be realised. Regarding the electricity transmission between regions, there is of course much more need in the transition pathways in both the high carbon tax and carbon-free targets scenarios to a similar degree, especially during the transition phase when the system is undergoing major modifications from 2030 to 2050.

In general, policy insights can be derived through the analysis using TAM. For example, the impact of the carbon tax was compared between two scenarios, the reference and the carbon tax scenarios, which showed that there was virtually no difference in the individualised behaviour of demand sectors such as the case for households and passenger transport. However, all sectors are able to decarbonise and reduce their **CO_2-equivalent emissions** in all scenarios with some sectors able to undertake efforts to a greater extent than others. In the reference (REF) scenario, emissions are reduced by 66.3% in 2050 compared to 2015. Compared to the reference scenario in the same time period, the carbon tax (CTX) scenario decreases the emissions by an additional 11.0% while the carbon-free targets (CFT) scenario decreases the emissions by an additional 28.4%, which emphasises that although imposition of high carbon taxes shifts the energy system towards a greater decarbonisation, without legislative or financial interventions it is still not enough to sufficiently drive the reduction in demand and production of emissions. Thus, fossil fuels will remain a significant fuel source well into the future and actors' potential in all sectors cannot be fully utilised to achieve the environmental targets. Emissions reductions in the harder to decarbonise sectors such as industry and passenger transport are only possible with an overall reduction in demand and investment in CCS technologies in industry as well as shifting to different modes in transport and incorporating carbon-free fuels like hydrogen. It is essential to overcome the high upfront investment costs which needs to be supported by a different kind of policy instrument.

Moreover, the objective of the policy scenario analysis was to assess the optimal distribution of centralised and decentralised energy technologies and this is measured through the overall **degree of decentralisation** in the energy system as the share of electricity self-generation in the demand sectors in total electricity generation throughout the whole system. Due to little incentive for electrification and use of alternative fuels, e.g., hydrogen, the potential of prosumers and hence the degree of decentralisation is overestimated in the reference (REF) scenario. With a shift from fossil fuels to electricity on the demand side in the high carbon tax (CTX) and the carbon-free targets (CFT) scenarios in order to mitigate emissions, the potential of the prosumers for self-generation seems to fade from what was seen in the reference (REF) scenario due to higher level of electrification. A decarbonisation by 2050 as investigated in the carbon-free targets (CFT) scenario requires massive electrifications and use of decarbonized fuels such as hydrogen produced via electrolysis. Therefore, the overall electricity demand spikes in this scenario and, as a result, the total decarbonisation is only possible through a decarbonised electricity generation by the supply sector, which supplements the increased self-generation in the demand sectors to meet the final demand. Thus, Increasing the shares of decentralised self-generation only works best in conjunction with an increased reliance on centralised energy supply such as electricity and district heating.

5.3. Conclusion

The TIMES Actors Model (TAM) proposes methodological extensions in sectoral models to enhance the modelling of actors' investment behaviour. For the TIMES family of models, these improvements fill the gap of representing the heterogeneity of investment and operation behaviour of actors. Therefore, provides an opportunity to investigate the investment potential in decentralised generation technologies. The coupling procedure developed in this study provides an opportunity to have a full picture of an integrated energy system, while maintaining a clear insight into each individual energy sector. The methodology has been developed and applied in the German energy system and would help to provide insights for concrete policy recommendations and identify an applicable roadmap for decarbonising the energy system, which will have maximum chances to be effectively implemented across relevant actors. The results in Section 3 show that the least-cost solution in the supply sector requires institutions and cooperatives to take on a more significant role than the incumbent utilities in investing in renewable generation technologies. With regards to the demand side sectors, the investor actors in industry should invest in CCS technologies or in improving the efficiency of sub-processes and buy electricity from the supply sector while households should invest in renewable-based power generation to avoid the additional cost burden posed by the carbon tax. Moreover, the actors providing the passenger transport services should invest in new transport technologies to furnish the required infrastructure fulfilling passenger transport demand. Following the German decarbonisation target by 2050 recently emphasised and debated in UN Summit 2019 (EURACTIV 9/24/2019), we have tested the impact of the carbon tax on the structure of power generation technologies. Analysing the results of carbon tax scenario reveals that in order to achieve an optimum structure of centralised and decentralised power generation, actors in the energy system should contribute in different levels: the actors in the supply sector should invest in CCS technologies as well as centralised renewables such as offshore wind parks. The CTX scenario would lead the residential sector to near-carbon neutrality (296.4 Kilotonne) by 2060. Therefore, incentives for the residential sector might speed up the full decarbonisation of the sector.

However, how these decisions continue to evolve for each type of actor depends on the prevailing conditions (e.g., energy price level and structure, policy) and the decision patterns (e.g., required payback periods, budgeting). Additionally, different actors are to be differentiated in the modelling process who face different framework conditions (e.g., energy and climate policy, regulatory, etc.) and corresponding patterns of behaviour both in investments and in the operation of facilities. TAM as an actor model, depicts the respective decision-making behaviour with regards to the investment in decentralised technologies and their use or the reaction to changes in residual load under the respective framework conditions.

5.4. Further use of the developed TAM model and future work

The TAM sector models have shown to provide insights in the different sectors and provide a platform to assess alternatives and micro-opportunities. Thus, with the help of the newly developed model approach, for example, questions about the importance of building renovation for the energy transition or a transport energy strategy can be studied in more detail. New approaches to the methodology for the coupling of different models, which appear to be transferable to other model couplings, can also be linked to the analysed coupling mechanisms. In addition, the temporal resolution in the models and in the individual models have potential for further development, which also has relevance for other systems-analytical studies. Furthermore, additional insights into the decentralisation potential of the German energy system and the necessary framework conditions can be explored under different aspects. From this, the design options of a smart, decentrally oriented energy system and its derived technological options can be derived with their economic, ecological and systemic potentials, including the resulting research and development needs, which take into account technical, economic and ecological as well as social aspects. Within the framework of the project, the qualification of young scientists is being pursued with the imminent conclusion of doctoral theses as was planned within the scope of the research project. In addition, new research findings are evaluated and developed further in future projects, for example, the BMWi funded, MANIFOLD project, and exploring other applications.

The TIMES Actor Model facilitates consideration of different actors' characteristics, potentials and limitations in each sector and still within the framework of integrated energy system investigations thanks to the coupling approach. Therefore, on the one hand TAM can be used competently as a tool to inform policies aimed at overall energy system transitions also showing the impacts of these policies on an actors level. On the other hand, TAM can also be applied to study how policy scenarios targeted at specific actors within a particular energy sector can affect other sectors and the overall energy system. Since sector models in TAM are separate, they can be utilised for studies limited to one or several specific sectors as well.

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Appendix

Methodology improvements for glass industry

<u>*Case Study: Disaggregation of actors in Glass*</u>

Actors in the glass industry were aggregated into six representative ‘actor groups’. Those companies that produce container glass were disaggregated by production size in two groups. Actors that flat glass were divided into two in the same manner. Moreover, special glass and fibre glass producers are represented in individual groups each. Figure A.1 shows the production outputs for actors in the glass industry and their respective ‘actor group’ while Table A.1 provides an overview of the resulting number of plants, companies and production that each ‘actor group’ represents.

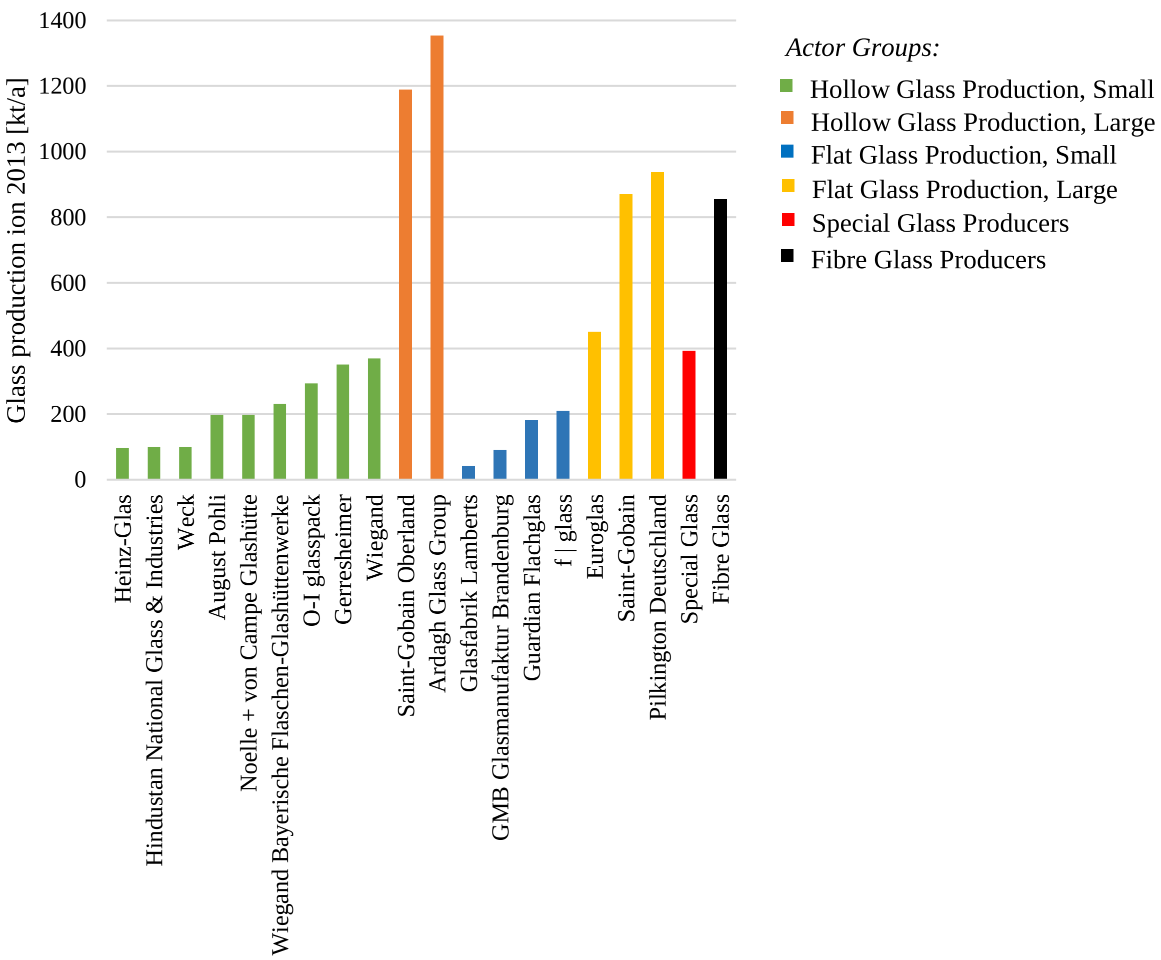

Figure A.1: Characterisation of actors in the Glass Industry, 2013

The technical representation of the production of glass is differentiated in four main groups, container glass producers, flat glass producers, special glass producers and fibre glass producers. As the account for the largest share, container glass producers and flat glass producers were further disaggregated into two groups each according to production size. The following improvements were implemented in the model.

Table A.1: Glass Actor Characterisation based on 2013 Production

Production	Production Capacity	Group Name	Plants	Companies	Production (kt/year)	Share (%)
Hollow	Small	**IGH1**		9	1935	20
	Large	**IGH2**		2	2542	26
Flat	Small	**IGF1**		4	552	6
	Large	**IGF2**		5	3504	36
Special	-	**IGSP**		-	393	4
Fibre	-	**IGFI**		-	855	8
Total	-	-			9781	100

Conceptual methodological improvements in TAM for the Glass Industry

Base year representation: TIMES PanEU represents glass production in one step for hollow glass, and one step for flat glass. It does not explicitly model special and fibre glass. In order to better show the differences of the production status among actor groups and understand how this differences affect their investment behaviour, the technical representation of hollow and flat glass production for the base year was expanded into 3 main production processes; batch preparation, melting, and forming, while special and fibre were modelled explicitly into one aggregated process each.

New Investments: Retrofits measures for Base Technologies: Options for investment in retrofit measures for process technologies with installed capacity in 2013 have been implemented in the model. Such measures result in the reduction of either electricity and/or fuel consumption. Table A.2 shows the measures implemented and their corresponding savings per ton of glass produced.

Table A.2: Retrofit measures and savings implemented in the TAM-Industry for Glass

Main Production Process	Production Process	Retrofit Measures	Electricity Savings	Fuel Savings	Investment Costs	Lifetime
			MJ/t_{steel}	MJ/t_{steel}	EUR2013/t_{steel}	years
	Batch preparation	Reduction of batch wetting (moisture content 3.5 to 2%)	11	113	0	99
		Increase in recycling to the technical maximum	1	14	1	99
	Melting	Change to regenerative U-flame tank from regenerative, cross-fired melting tank	20	200	175.9	12
		Oxygen burner for regenerative melting tanks	-231	888	105.5	12
		Reduction of excess air through improved lambda control	13	129	2.3	15
		Reinforced insulation	40	399	4.8	15
		Change to regenerative U-flame tank from recuperative melting tank	134	1337	175.9	12
	Forming	Optimised forehearth control through infrared analysis	8	83	0.8	15
Flat	Batch preparation	Increase in recycling to the technical maximum	0	40	1	99
		Reduction of batch wetting	11	113	0	99
	Melting	Oxygen burner for regenerative melting tanks	-420	1615	105.5	10
		Reduction of excess air through improved lambda control	0	249	2.3	15
		Reinforced insulation	0	549	12.7	15

New Investments: 'Best Available Technologies/Measures': The following best available technologies (BATs) and measures were identified and implemented in the model as shown in Table A.3.

Table A.3: Best Available Technologies/Measures for Glass

Main Production Process	**Production Process**	**Best Available Technologies/Measures**
Hollow	Batch preparation	Recycling to the technical maximum and reduction of batch wetting
	Melting	Regenerative U-flame tank with reinforced insulation
	Forming	Optimised forehearth control through infrared analysis
Flat	Batch preparation	Recycling to the technical maximum and reduction of batch wetting
	Melting	Oxygen burner for regenerative melting tanks with reinforced insulation

New Investments: Decentralised Technologies: Regarding investments in decentralised energy production, the following technologies for glass production were considered:

- *Furnace waste heat generation using a steam engine*
- *Furnace waste heat generation using an ORC system*
- *CHP system*
- *Rooftop PV*
- *Biomass gasification for Hydrogen production*
- *Electrolysis for Hydrogen production*

Methodology improvements for cement industry

Case Study: Disaggregation of actors in Cement

Actors in the cement industry were aggregated into five representative 'actor groups'. Cement producers are differentiated into two main groups, those with integrated production and those with non-integrated production. Integrated production consists of raw materials extraction, grinding and homogenization, and includes clinker production as well as cement grinding and finishing while non-integrated production does not include clinker production but rather starts with clinker as main raw material. Therefore, it consists only of cement grinding and finishing to the different cement grades. Figure A.2 shows the production outputs for actors in the cement industry and their respective 'actor group' while Table A.4 provides an overview of the resulting number of plants, companies and production that each 'actor group' represents.

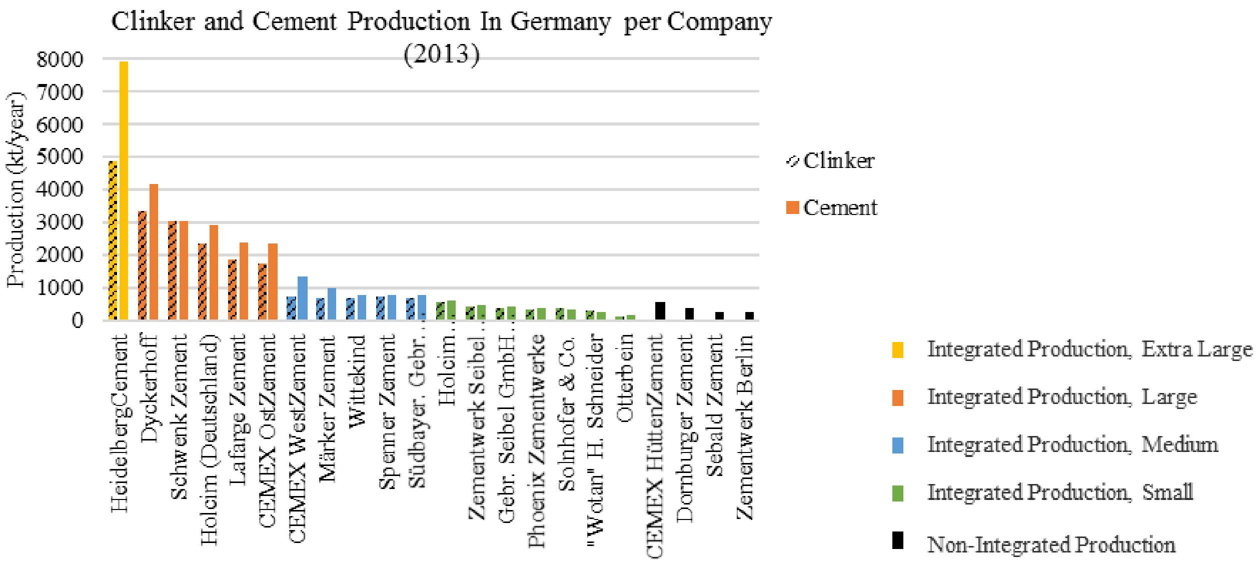

Figure A.2: Characterisation of actors in the Cement Industry by production route and levels, 2013

Table A.4: Cement Actor Characterisation based on 2013 Production

Production Type	Production Capacity	Actor Group Name	Plants	Companies	Production (kt/year)	Share (%)
Integrated	Extra Large	ICM_XI	10	1	7,918	25.3
	Large	ICM_LI	21	5	14,881	47.5
	Medium	ICM_MI	10	5	4,569	14.6
	Small	ICM_SI	7	7	2,548	8.1
Non-Integrated	-	ICM_NI	4	4	1,387	4.4
Total			***52***	***22***	***31,303***	***100***

Conceptual methodological improvements in TAM for the Cement Industry

The following improvements were implemented in the model.

Base Year Representation: TIMES PanEU represents cement production into two steps, clinker production and cement finishing. These two process are used as an aggregated representation of all other processes involved in the production route. In order to better show the differences of the production status among actor groups and understand how this differences affect their investment behaviour, the technical representation of cement production for the base year was expanded to include more detail. The original wo processes from TIMES PanEU were disaggregated into 8 main production processes, raw material grinding, homogenization, conveyer system, preheater, pre-calcinator, kiln, cooler, and cement grinding. Within each off the existing capacities were identified and represented according to the type of technology employed. For example, for raw material grinding, there are two types of installed capacity in the base year, vertical mills and ball mills. Ultimately, the representation of the cement industry in the base year grew from two processes (as represented in TIMES PanEU) to a total of 23 processes.

New Investments: Retrofits measures for Base Technologies: Options for investment in retrofit measures for process technologies with installed capacity in 2013 have been implemented in the model. Such measures result in the reduction of either electricity and/or fuel consumption.

Table A.5 shows the measures implemented and their corresponding savings per ton of cement produced.

Table A.5: Retrofit measures and savings implemented in the TAM-Industry for Cement

Main Production Process	Production Process	Retrofit Measures	Electricity Savings	Fuel Savings	Investment Costs	Lifetime
			MJ/t_{steel}	MJ/t_{steel}	$EUR2013/t_{steel}$	years
Raw Material Preparation	Grinding	Replacement of ball mills with vertical mills	40	0	9.8	20
	Homogenization	Raw meal homogenization in gravity silos	10	0	3	25
	Conveyer system	Mechanical instead of pneumatic conveyor systems	11	0	8.7	20
Clinker Production	Preheating	Low pressure loss cyclone preheater	9	0	3.7	20
		Expansion of the cyclone preheater to five stages	0	90	4	20
	Pre-calcinator	Retrofitting of the pre-calciner on the rotary kiln with cyclone preheater	0	430	22.6	40
	Kiln	80% use of secondary fuel	-3	-300	5	20
		Replacement of Lepol furnaces with rotary kilns with cyclone preheater and calciner	18	900	85	40
	Cooler	Change from rotary or satellite cooler to grate cooler	-13	200	8.8	20
		Modernization of grate cooler too Chill grate cooler	0	25	0.8	20
Cement Production	Grinding	Increase in blast furnace slag usage	0	183	0.3	20
		Replacement of ball mills with vertical mills	93	0	15.3	20
		Improved type of grinding balls	22	0	1.7	10
		Increase in the use of fly ash	97	600	0.1	20

New Investments: 'Best Available Technologies/Measures': The following best available technologies (BATs) and measures were identified and implemented in the model as shown in Table A.6.

Table A.6: Best Available Technologies/Measures for Cement

Main Production Process	**Production Process**	**Best Available Technologies/Measures**
Raw Material Preparation	Grinding	Vertical mills
	Homogenization	Raw meal homogenization in gravity silos
	Conveyer system	Mechanical conveyor systems
Clinker Production		5 stages cyclone preheater
	Pre-calcinator	Use of pre-calciner
	Kiln	80% use of secondary fuel
		Rotary kilns
	Cooler	Grate cooler
Cement Production	Grinding	Use of blast furnace slag
		Vertical mills with decreased clinker ratio
		Use of fly ash

New Investments:' Innovative Technologies/Measures': The following innovative investment options for cement production technologies identified to potentially play a key role in the future decarbonisation of the cement industry were implemented in the model:

- *Innovative hydraulic binder*
- *Innovative hydraulic binder with CCS*
- *Novel Cements: Celitement*

New Investments: Decentralised Technologies: Regarding investments in decentralised energy production, the following technologies for cement production were considered:

- *CHP system*
- *Rooftop PV*
- *Biomass gasification for Hydrogen production*
- *Electrolysis for Hydrogen production*
- *Electricity generation from waste heat*