Local Emissions for Net Zero (LENZ) Modelling Suite – Toronto

Technical documentation

Version 1.0 – August 2023

For the City of Toronto

Photo by Scott Webb from Pexels

Acknowledgements

Land acknowledgement

The City of Toronto acknowledges that we are on the traditional territory of many nations including the Mississaugas of the Credit, the Anishnabeg, the Chippewa, the Haudenosaunee, and the Wendat peoples and is now home to many diverse First Nations, Inuit, and Métis peoples. The City of Toronto also acknowledges that Toronto is covered by Treaty 13 signed with the Mississaugas of the Credit, and the Williams Treaties signed with multiple Mississaugas and Chippewa bands.

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About the project team

ESMIA Consultants

ESMIA provides expertise in 3E (energy-economy-environment) integrated system modelling for deriving and analyzing optimal economic, energy and climate strategies. ESMIA puts forward a scientific approach guided by sophisticated mathematical models. The goal behind our implication is to offer solutions that allow achieving energy and climate goals without compromising economic growth. For 20 years, the ESMIA consultants provide a full range of services for the development of economy-wide energy system models for high-profile organizations worldwide. They also provide advisory services that focus on analyzing complex problems such as energy security, electrification, technology roadmap and energy transitions. ESMIA benefits from its own integrated suite of models, including in particular: The North American TIMES Energy Model (NATEM) combined with the North American general Equilibrium Model (NAGEM).

Sustainable Energy Systems Integration and Transition Group (SESIT)

The Sustainable Energy Systems Integration and Transitions Group (SESIT) is led by Madeleine MacPherson at the University of Victoria. The group focuses on energy systems integration – the process of coordinating the operation and planning of our energy systems over a variety of spatial-temporal scales and infrastructure systems (transport, buildings, electricity, water). Their work involves the development and application of energy system software, designed to address research and policy questions related to variable renewable energy integration, demand response initiatives, utility-scale and behind-the-meter storage technologies, and electric vehicle integration.

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We acknowledge the support provided by the Technical Advisory Group for the development and application of LENZ.

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List of acronyms

ACRONYM	DEFINITION
3E	Energy-economy-environment
CO_2	Carbon dioxide
CSV	Extension .csv
db	Database
EV	Electric vehicle
GDP	Gross domestic product
GHG	Greenhouse gas
ICE	Internal combustion engine
IESO	Independent Electricity System Operator
LENZ	Local Emissions for Net Zero Modelling Suite - Toronto
IPYNB	Extension .ipynb
NATEM	The North American TIMES Energy Model
NZS	Net Zero strategy
O_3	Ozone
OEB	Ontario Energy Board
PNG	Extension .png
PV	Photovoltaic panel
RNG	Renewable natural gas
SILVER	Strategic Integration of Large-capacity Variable Energy Resources
SILVER-TO	Strategic Integration of Large-capacity Variable Energy Resources - Toronto
SQLITE	Extension .sqlite
TEDI	Thermal energy demand intensity
TEUI	Thermal energy use intensity
TEMOA	Tools for Energy Model Optimization and Analysis
TEMOA-TO	Tools for Energy Model Optimization and Analysis - Toronto
TGS	Toronto Green Standard
TOU	Time-of-use

List of scenarios

ACRONYM	DEFINITION	Modelled with
DON	Do-nothing	LENZ
BAP-TTO	Business-as-planned	LENZ
NZ40-OPT	Net Zero by 2040 – Optimal	LENZ
NZ40-TTO	Net Zero by 2040 – TransformTO	LENZ
NZ50-OPT	Net Zero by 2050 – Optimal	LENZ
NZ50-TTO	Net Zero by 2050 – TransformTO	LENZ
BAP	Business-as-planned	CityInsight
NZ40	Net Zero by 2040	CityInsight
NZ50	Net Zero by 2050	CityInsight

List of units

UNIT	DEFINITION	MEASURE OF:
h	Hour	time
km	Kilometre	distance
V	Volt	Electricity voltage
kV	Kilovolt	Electricity voltage
t CO_2e	Tones of CO_2 equivalent	Emissions quantities
Mt CO_2e	Million tones of CO_2 equivalent	Emissions quantities
kW	Kilowatt	Power
MW	Megawatt	Power
GW	Gigawatt	Power
MW/h	Megawatt per hour	Load ramp
MWh	Megawatt hour	Energy
TJ	Terajoule	Energy
CA$	Canadian dollars	Currency
cap	Capita	Number
act	Activity	Activity value

Glossary

TERM	DEFINITION
Capacity expansion model	Model that is used for long-term planning in the GHG emitting system. This model allows to identify least-cost solutions in terms of future investments in energy and waste system given multiple factors such as demand projections, technology performance and costs, fuel prices and new policies. e.g., Tools for Energy Model Optimization and Analysis – Toronto (TEMOA-TO)
Cost factor	Factor that takes into account operation cost of a specific generator type.
Curtailment	Electricity curtailment is the deliberate reduction of electricity generation (typically from renewable technologies) below the level that can be produced to balance electricity supply and demand.
Demand ratio	Electricity demand for a reference year normalized by the total demand of the respective season (i.e., winter, spring, summer or fall). It is use in the Linking Tool to automatically convert the total seasonal demand optimized by TEMOA-TO into seasonal hourly demand profiles and accounts for a possible peak shift.
Energy mix	Combination of different sources of energy that a country or region uses to meet its energy needs.
Energy Service Demand	Term used in energy modeling to refer to the service that is provided by energy (typically through the technologies), which is separated from the energy itself. For example, people want to travel from one place to another. They use energy (e.g., gasoline) for this service but the demand is for the service itself rather than a particular fuel. Thus, gasoline use can be replaced by electricity or physical activity to meet the same service (travel). In Section 1 of this document the term *Energy Service Demand* is often substituted by *Demand* for clarity purpose.
Greenhouse gas	Gases that trap heat in the Earth's atmosphere and contribute to the greenhouse effect. These gases are naturally present in the atmosphere but human activities, especially fossil fuel combustion and deforestation, are significantly increasing their concentration (anthropogenic greenhouse gases).
LENZ Modelling Suite – Toronto (LENZ)	A suite that comprises more than one model interacting via internal or external links (i.e., requiring the intervention of the user). *The LENZ Modelling Suite – Toronto is referred to as LENZ all through this document.* e.g., TEMOA-TO + the Linking Tool + SILVER-TO
Linking tool	A tool that ensures communication between the two or more models to maximize their complementarity and to reinforce the value for decision-makers. e.g., the Linking Tool for passing TEMOA-TO output to SILVER-TO

TERM	DEFINITION
Load ramp	Load ramp provides an indication about the speed of electricity load change. Load ramp-down, referring to the speed of load decrease (MW/h), is typically associated with the load decrease from the morning peak to the intra-peak load level (around midday for current load profile). Load ramp-up, referring to the speed of load increase (MW/h), is typically associated with the load increase from the intra-peak load level to the evening peak.
Net load	Net load of the city refers to the difference between the total electricity demand, and the distributed electricity generation connected at the distribution grid level and must be supplied by the transmission system. A particular case of a PV generation effect on electricity demand is the net load reshaped as a duck belly (so-called duck curve effect).
Net Zero	Equilibrium where the quantity of greenhouse gases emitted is offset by the amount that is removed from the atmosphere and stored.
Optimal power flow	Optimal power flow represents the non-linear problem of determining the best operating levels for electric power plants to meet demand given throughout a transmission network by minimizing total operating cost.
Optimal dispatch	Optimal dispatch is the optimal allocation of individual generating units (units' commitment) to produce electric power at the lowest cost to reliability serve consumers, recognizing any operational limit of generation and transmission facilities.
Optimality	System configuration or net zero pathway which represented the lowest cost solution (or minimum cost solution) for satisfying service demands under various constraints.
Optimization model	Computational framework used to identify the optimal solution among a set of possible alternatives, subject to constraints and objectives, in order to maximize or minimize a specific outcome.
Peak load	Peak load is the highest amount of electric power that consumers (here the city) draw from the grid in a set period of time (here one hour).
Production cost model	A model that is used for short-term planning in the electricity sector. These models allow to identify least-cost solutions in terms of electricity produced by different generation units and electricity production costs of a given power system, given multiple factors such as temporal and geographic load distribution, generating unit locations, and transmission constraints. They simulate unit commitments and optimal dispatch. e.g., Strategic Integration of Large-capacity Variable Energy Resources – Toronto (SILVER-TO)
Renewable energy	Energy source that is naturally replenished and can be used repeatedly without the depletion of resources (also called clean energy).
Resilience (energy)	The ability to avoid, prepare for, minimize, adapt to, and recover from anticipated and unanticipated energy disruptions in order to ensure energy availability sufficient to cover demand.

TERM	DEFINITION
Scope 1 emissions	GHG emissions from sources located within the city boundary.
Scope 2 emissions	GHG emissions occurring as a consequence of the use of grid-supplied electricity, heat, steam and/or cooling within the city boundary.
Scope 3 emissions	All other GHG emissions that occur outside the city boundary as a result of activities taking place within the city boundary.
Secondary energy	Energy that has been transformed from its primary source and is used for various end-use applications. Examples include electricity generated from coal or gasoline derived from crude oil.
Self-consumption	Self-consumption refers to producing and using the same electricity at one site, for example, using electricity generated by solar panels installed at a consumer's premises to provide electricity for that location.
Simulation model	Computational representation of a real-world system or process used to understand and explore its potential behaviour under different scenarios or conditions.
Solar shading	Obstruction of sunlight on PV panels (caused by trees, buildings, or other structures) that directly affects the overall electricity generation of PV panels.
Unit commitment	Unit commitment is the process of selecting the units from the available generators to meet the power demand.

Project overview

In December 2021, the City of Toronto adopted its TransformTO Net-zero Strategy (NZS) [1] that aims to outline a pathway to reach net zero greenhouse gas (GHG) emissions by 2050 or sooner. Technical Report[2] of the NZS contained the analysis of the technical, financial, and social/behavioural feasibility of the proposed climate actions. In this context, four main scenarios had been developed using the CityInsight[3] simulation model to identify priorities in terms of climate actions: “Do-Nothing”, Business as Planned (BAP), Net Zero by 2050 (NZ50) pathway, and Net Zero 2040 pathway (NZ40).

A subsequent project was undertaken to develop the Local Emissions for Net Zero (LENZ) modelling suite – Toronto (or LENZ as it is referred to in this document). LENZ is based exclusively on open-source tools and code for greater transparency, to support the City with the implementation of its NZS and to bring regular adjustments to existing and future policies for meeting the net zero 2040 target more efficiently.

LENZ is based on a dual-scale approach including both long-term capacity expansion model and a short-term production cost model for the City of Toronto, as well as a Linking Tool connecting the two models (Figure 1).

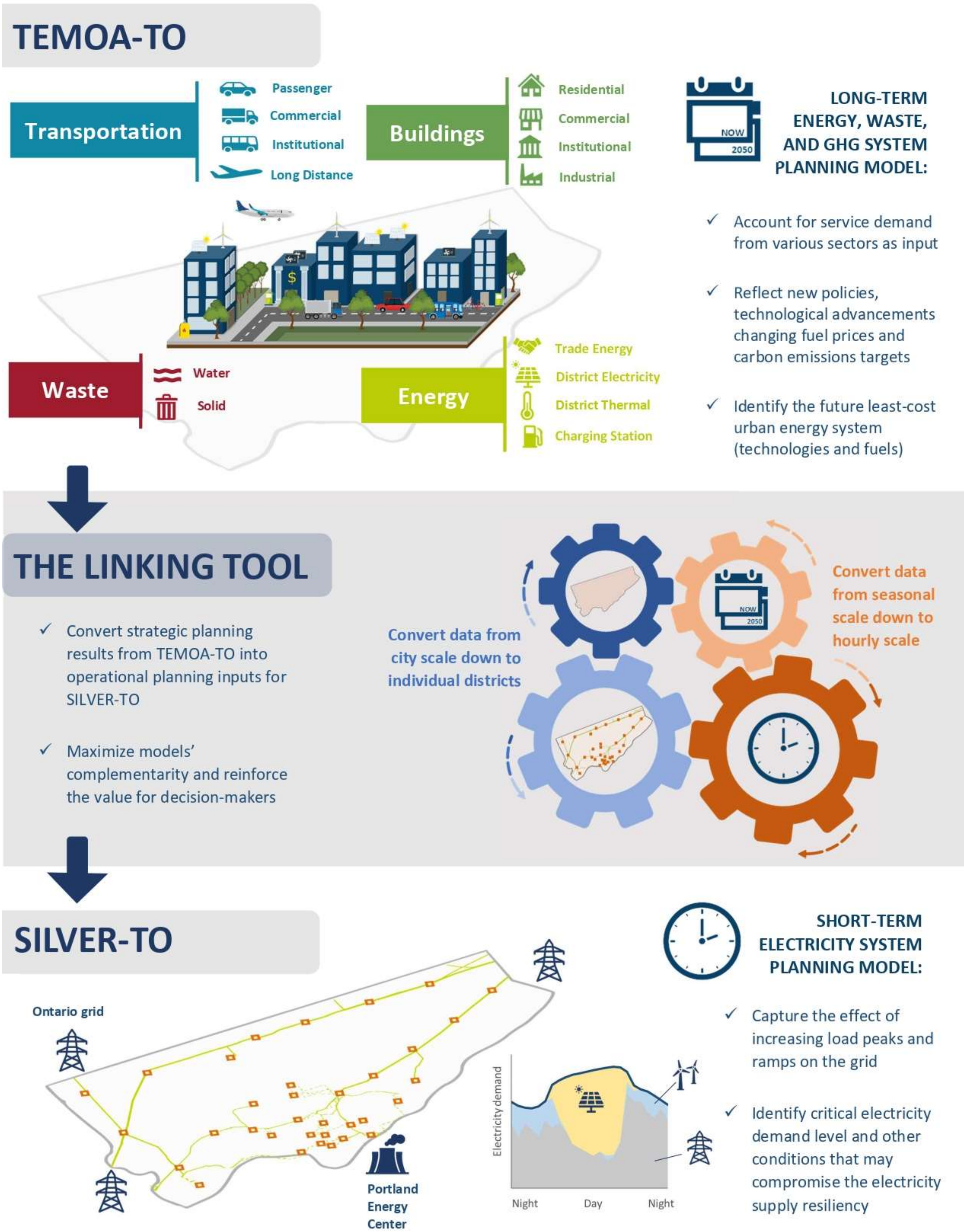
To use LENZ, 3 other software are mandatory. The first essential software is Python Language which should be of version 3 or higher. Additionally, it is necessary to have Anaconda software installed on your computer. Lastly, since the Tools for Energy Model Optimization and Analysis – Toronto (TEMOA-TO) and the Strategic Integration of Large-capacity Variable Energy Resources – Toronto (SILVER-TO) are optimization models, a solver is needed. Section 1.6.3 describes several available solvers. Detailed installation instructions for all of these software programs can be found in ANNEX C.

[1] City of Toronto (2021). TransformTO Net Zero Strategy: A climate action pathway to 2030 and beyond. 136p. https://www.toronto.ca/legdocs/mmis/2021/ie/bgrd/backgroundfile-173758.pdf

[2] City of Toronto (2021). TransformTO Net Zero Strategy Technical Report. 107p. https://www.toronto.ca/wp-content/uploads/2022/04/8f02-TransformTO-Net-Zero-Framework-Technical-Report-Parts-1-2.pdf

[3] SSG - Sustainable Solutions Group (2023). Tools: CityInsight. Online (Accessed in June 2023): https://www.ssg.coop/tools/

Figure 1. Architecture of LENZ



The goal of this technical documentation is to provide a detail description of the three models and their main functionalities, as well as instructions on how to use them for scenario analysis. Details for each of those three models are given in the next three sections of the document respectively.

Long-term energy and waste system and GHG planning models excel at tracking changes in installed technology – for example, purchases of new technology as the economy expands, the old technology retires, or new manufacturing needs emerge. These models (also known as capacity expansion models) typically cover the time of investment planning cycles, several decades for energy and waste system investment (such as 2016-2050 for this project). Therefore, long-term planning models, such as TEMOA-TO, are perfect for the development of net zero transition plans. By using this model, the decision-maker will be able to address questions like:

- How should the energy mix evolve and what type of energy must increase or decrease?
- What type of capacity should be added or retired?
- When should investments be made?

TEMOA-TO tracks changes to the GHG emitting sectors by identifying the least-cost mix of energy and waste system resources (technologies and fuels) to meet a projected energy demand, taking into consideration new policies, technological advancement, changing fuel prices and carbon emission constraints. To do this, TEMOA-TO identifies and imports the total energy production required to address energy demands in Toronto. The model is built annually; however, it would require tremendous calculation power to solved it annually from 2016 to 2050 in a realistic time. By default, the resolution used is a one-year basis from 2016 to 2025, and five-years increment until 2050, which provide a good balance between solving time and period resolution.

However, long-term energy system and GHG planning models are not able to capture the full spectrum of the operation decisions that happen within one year. This disadvantage is a particular challenge for modelling the electric sector. The solution identified by TEMOA-TO, which is based on the total power generation over a year, may be not ideal for short-term operations (e.g., at hourly, daily basis). A common example is in the case of renewable energy generators, such as solar photovoltaic panel (PV) generators, operating under net metering can increase the load ramp-up and ramp down on the grid, which requires additional investment to balance the variations and protect the grid equipment.

To address these issues, LENZ includes the short-term planning model SILVER-TO, developed for evaluating the impact of high variable renewable penetration on electricity grids. The model takes the electricity system configuration of Toronto, including power demand and generator centers, as well as transmission and distribution infrastructure, renewable generation, and demand profiles, and identifies the least-cost balancing strategy, as well as infrastructure risks and weak points. SILVER-TO uses hourly resolution for solving optimal power flow problem to optimize power generation unit commitment (optimal power dispatch) under various constraints, such as generator minimum output, transmission stability and voltage constraints. SILVER-TO is structured to address power production and consumption balancing, reliability of power grid and potential stress on the existing power grid, that may become vulnerable to blackouts.

Optimal power flow models such as SILVER-TO are also limited by the extent of their operational planning horizon due to the same computational limits as for long-term planning models. Power flow models address this limit by typically covering shorter periods, such as a one-year period. By using this model, the decision-maker will be able to address questions like:

- When/how should power generators operate the equipment to meet power demand?
- What is the role of electric storage and what are optimal charging/discharging strategies?
- Will the transmission grid be able to ensure a resilient supply of electric power to address future demand under increasing demand peaks?

The Linking Tool is used to exchange data between TEMOA-TO and SILVER-TO, allowing the user to generate SILVER-TO inputs from TEMOA-TO results. In this way, a yearly capacity expansion plan for Toronto can be broken down and assigned to power infrastructure nodes depending on real constraints. For the inputs to TEMOA-TO from SILVER-TO, the Linking Tool transforms possible operational risks into recommendations that the decision-maker may use for the consequent run of TEMOA-TO. Linking both models is the key to identifying the least-cost pathway for GHG emitting sectors evolution in Toronto that is also operationally reliable and less costly.

1. TEMOA-TO

1.1 The TEMOA platform as the core model

The TEMOA-Toronto (TEMOA-TO) model is based on the energy optimization toolbox named Tools for Energy Model Optimization and Analysis (TEMOA).

1.1.1. Energy and waste system design

Energy system and greenhouse gases (GHG) emissions planning models, like TEMOA, use the key concept of system networks which refer to the boundaries, connections and content of the system modelled (Figure 2). Simplified schematic networks are commonly used to represent the modelled system, where boxes represent technologies or groups of technologies, circles represent commodities and arrows represent flows of commodities between technologies:

- **Technologies** (or processes): Any devices that produce, transform, transport, distribute and consume energy. Examples of technologies include vehicles (transport sector), heat pumps (building sector) and biodigesters (waste sector). In addition, the model database includes existing technologies, improved versions of the same technologies and emerging technologies, all characterized by their technical and economic attributes.

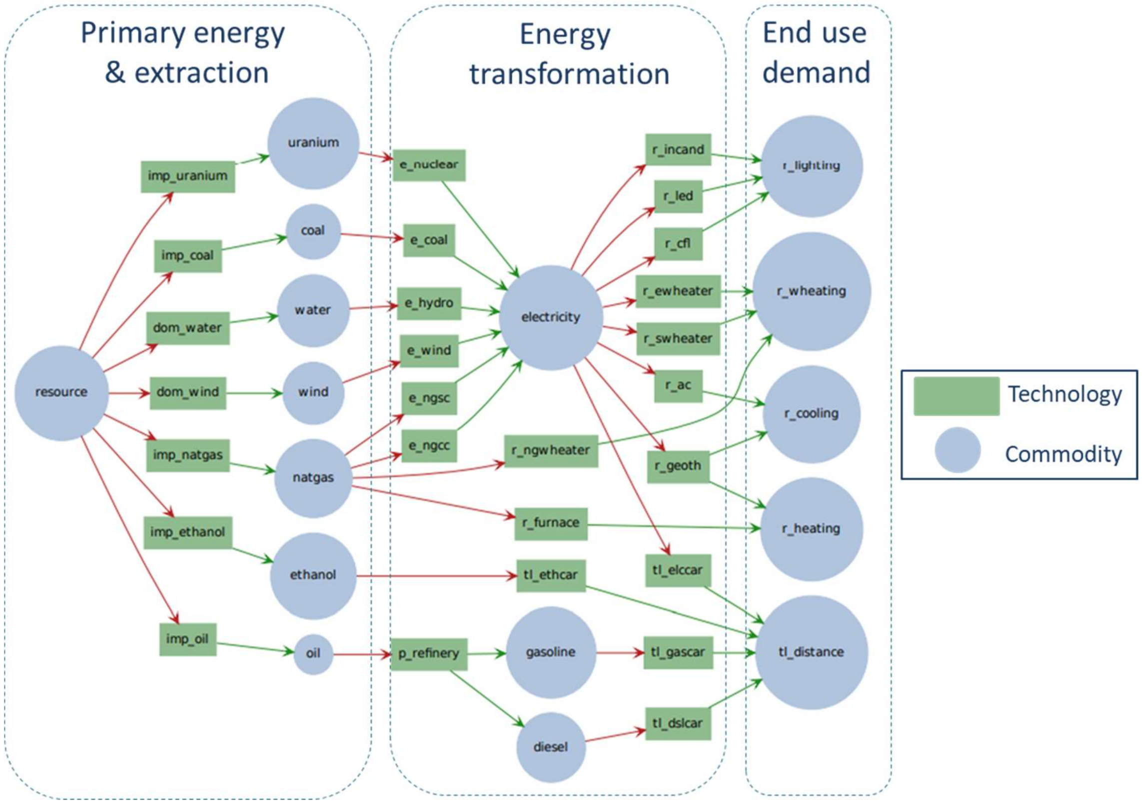
  Some technologies are complementary and form chains (e.g., a heat pump that uses electricity needs this electricity to be produced by a power plants), while others are in competition to supply the same commodities or demands (e.g., a household can choose a heat pump or a furnace to heat its house).

- **Commodities**: All energy forms, materials, demands and emissions that are produced or consumed by technologies.

After the initial design of the system (composed of energy and non-energy sectors), the modelling process involves the characterization of existing and future technologies with their technical and economic attributes as well as pollutant coefficients. Exogenous end-use demands are then projected over the long-term horizon (e.g., 2050) in physical units (e.g., passengers- and tons- kilometres for transport segments) using a coherent set of socio-economic projections (GDP, population, etc.) from official sources and other factors such as future announced projects. This is the starting point of the model: the model will optimize the technology mix in all supply and demand sectors to meet end-use demands at the least cost.

> “TEMOA is an energy system optimization model (…) that optimizes the installation and utilization of energy technology capacity over a user-defined time horizon. Optimal decisions are driven by an objective function that minimizes the cost of energy supply. Conceptually, one may think of an ESOM as a “left-to-right” network graph, with a set of energy sources on the left-hand side of the graph that are transformed into consumable energy commodities by a set of energy technologies, which are ultimately used to meet demands on the right-hand side of the network graph.”
>
> J. DeCarolis – TEMOA lead

Figure 2. Simplified representation of a fictive energy system



1.1.2. Energy and waste system optimization

Once the energy and waste system is characterized and demands are projected on the long-term horizon, model runs can be launched to solve for least-cost solutions. The optimization program of TEMOA comprises three components that we will refer to in the remaining portion of the document.

- The first component (objective) corresponds to minimizing the net total discounted cost of the entire energy and waste system modelled;
- The second component (endogenous decision variables) corresponds mainly to future investments and activities of technologies at each time period, the amount of energy produced or consumed by technologies, as well as energy imports and exports;
- The third component (constraints) corresponds to various limits (e.g., amount of energy resources available, allowable GHG emissions in each year) and obligations (e.g., energy balances throughout the system, useful energy demand satisfaction) to be respected.

In summary… TEMOA solves by mathematically determining (decision variables) the mix of technologies (from the techno-economic database) that meet the energy service demands (inputs), subject to constraints such as government policies and resource availability, *at the least cost* over the full planning horizon.

Results include the optimal energy and waste system configuration from end-use demand to energy supply sectors as well as GHG emissions. Examples of results are provided in Section 5.

1.2 TEMOA platform native anatomy and project specific upgrades

In this section we will provide more details on the specific functionalities of the TEMOA modelling platform. Each modelling platform has its own terminology and specifications. We explain the most important elements to understand and to keep in mind when developing and using models with this platform. For more exhaustive information on the different parameters please refer to the TEMOA documentation.

1.2.1. Start building the database

The model development starts by providing information for all dimensions. Table 1 describes the dimensions used within TEMOA, namely the spatial and temporal resolution as well as the details in terms of technologies and commodities.

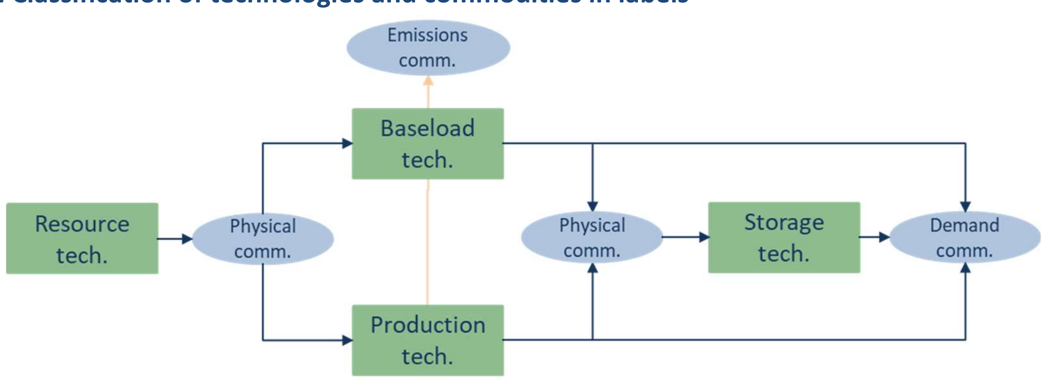
Table 1. Set used in TEMOA

Dimension	Description
Region	The spatial granularity considered is **one zone** representing the entire Toronto.
Time period	Base year: 2016 ○ 2016-2030 **annual** ○ 2030-2050 **5 years**
Time season	**4 seasons** are modelled: Summer, Fall, Winter, Spring
Time day	**4 intra-day** periods are modelled: Day, Night, Peak 1, Peak 2
Technology	List of all technologies
Commodity	List of all commodities

1.2.2. Assign default labels to time periods, technologies, and commodities

The modelling continues with the assignment of a default label to each **time period, technology, and commodity**. Default labels are used in the core code and cannot be changed as it would lead to a multitude of compilation errors. Figure 3 shows possible labels for technologies and commodities and their interrelations.

Figure 3. Classification of technologies and commodities in labels



There are two possible labels for time periods: existing years and future years.

There are three possible labels for commodities: energy service demands, emissions commodities, and physical commodities. Energy service demands are exogenous variables (input of the model), while emission commodities and physical commodities are endogenous variables (optimized by the model).

1. **Energy service demands (referred as demand for simplicity)** are quite detailed and vary from, for example, the floorspace of a given type of building, to the distance travelled for commuting transportation.;
2. **Emissions commodities** include any emissions to the environment from pollutants to greenhouse gases or waste heat;
3. **Physical commodities** cover all other commodities.

There are four possible labels for technologies:

1. **Resource technology** representing the extraction of raw materials from a reserve;
2. **Baseload technology** which has a constant production within a season;
3. **Storage technology** allowing the system to spare excess energy to release it later;
4. All other technologies labelled as **production technology**.

Note that every technology label is subject to a different set of constraints and equations.

1.2.3. Characterize technologies and commodities

After defining the core information, the modelled system must be defined. In TEMOA, the system is composed of elements which are technologies linked from one to another with commodities. The amount of a technology is called its *capacity* while the flow of commodity is called an *activity*. The Table 2 illustrates examples of technologies and commodities. A complete overview of the architecture and the way technologies are linked with one another is provided in section 3.4.

Table 2. Examples of technologies and commodities

Sector	Input commodity	Technology	Output commodity
Building	Grid electricity	Heat pump standard efficiency	Space Heating energy
Building	Space Heating energy	Apartment built in 1950	Square metres
Transportation	Gasoline	Hybrid light truck gasoline	Passenger kilometres
Transportation	Hydrogen	Hydrogen freight train	Ton kilometres
Waste	Natural gas	Anaerobic digester	Tons of waste treated
Local Energy	Solar energy	Photovoltaic panel optimal location	Local electricity

To define any element, specific information is required, by order of importance:

Demand parameters:

- **Demand** means future year projection of end-use commodities;
- **DemandSpecificDistribution** between time slices. By default, demand is evenly distributed;
- **GlobalDiscountRate**, used for defining contribution of annual versus lifetime costs in the least cost solution, by default 0.05.

Critical parameters to define a technology:

- **Efficiency** of a technology representing the linear factor between input and output; It is the most critical data as a technology does not exist if its efficiency is not filled;
- **CapacityToActivity** represents the link between technology and activity in the context "How much activity would this capacity create, if used 100 per cent of the time?";
- **CostInvest** is the investment cost to install 1 unit of capacity; this must be filled to let the model invest in a technology.

Important parameters to define a technology:

- **EmissionActivity,** quantity of emissions produced for 1 unit of output activity;
- **CapacityFactor,** rate representing the quantity of output in each time slice under the theoretical maximum output in the same time slice. By default, its value will be 100 per cent;
- **LifetimeTech** represents the lifetime of a technology; default value is 13 years;
- **CostFixed** representing the annual fixed cost for a unit of an installed capacity;
- **CostVariable** representing the cost for a unit of activity produced.

Optional parameters to define a technology:

- **DiscountRate** overwrite the global discount rate for a specific technology;
- **StorageDuration** defines the discharge time at full load time of a storage technology;
- **Lifetime loan** gives the possibility of decorrelate loan lifetime with technology lifetime, by default the technology lifetime is assigned;
- **Capacity credit** fraction of installed capacity that can be relied on during electricity peak load.
- **Reserve margin** capacity reserve margin to handle electricity peak load;
- Additionally, technology can be added to sets as **tech_curtailement** or **tech_flex** allowing overproduction of a commodity by a technology.

As an example, the following table describe simplified parameters value for a gas boiler, for more extensive information please refer to the model files.

Table 3. Typical parameter values for a natural gas boiler

Sector	Value	Unit
Technology	Gas Boiler	
Input commodity	Natural gas	
Output commodity	Space Heating	
Efficiency	95	%
CapacityToActivity	31.53	TJ / MW
EmissionActivity	40	t CO_2 / TJ
CapacityFactor	95	%
LifetimeTech	15	years
CostFixed	10	CA$ / kw / y
CostInvest	2000	CA$ / kW

1.2.4. Define physical constraints

While TEMOA includes several core flow constraints which are part of the original TEMOA model code, and not possible to be modified by the user, it does allow the user to design other flow constraints. The core constraints define derived decision variables, the algebraic formulation of the energy and waste system network, and assure that the system follows physical rules. The first step for defining new user constraints is to define the existing systems, and the technologies to invest in.

ExistingCapacity constraints force the model to include a capacity of a technology at the beginning of optimization time.

TechInputSplit and **TechOutputSplit** constraints fix the input/output minimum share of a commodity in a period. If a technology has multiple input commodities but no share to be fixed, this constraint should not be filled (e.g., a natural gas furnace can use renewable or standard natural gas without specific share constraints).

1.2.5. Define policy constraints

The goal of developing a long-term planning model is to develop policies. TEMOA includes a set of native user specific constraints which are useful to design policies. Those constraints are related to physical flows and capacities (Table 4).

Table 4. List of native policy constraints

Dimension	Description
MaxCapacity MinCapacity	Represents an upper/lower bound on the total installed capacity of a given technology in each model period.
MaxCapacitySum MinCapacitySum	Represents an upper/lower bound on the total installed capacity of a given technology across all periods.
GrowthRateSeed	Defines the maximum capacity of a given technology when first installed in a period.
GrowthRateMax	Defines the maximum annual rate at which the capacity of a given technology can grow
MaxActivity MinActivity	Constrain the upper/lower bound of total activity from a given technology in each model time.
EmissionLimit	Represents an upper bound on the emission that can be released in a specific period (Unit: t / year)
MaximumResource	Represents an upper bound on the cumulative amount of commodity that can be produced by technology over the model time horizon.
ResourceBound	This parameter allows the modeller to specify commodity production limits per period.

GrowthRateMax and **GrowthRateSeed** defines the maximum growth rate of a technology capacity among periods. This constraint is slightly turned for the project, it allows 2 types of growth rate:

Table 5. Growth rate parameters values and impact on technology maximum growth rate

#	GrowthRateMax (GRM)	GrowthRateSeed (GRS)	Impact on maximum growth rate
1	Unfilled	Unfilled	Unbounded technology capacity growth
2	Null	Not Null	Linear maximum capacity growth with a maximum of GRS
3	Null	Null	Technology ban
4	Not Null	Not Null	Exponential growth rate with an initial value of GRS and an annual maximum increase of GRM
5	Not Null	Null	Technology ban

Other parameters, in particular economic ones, are not native in TEMOA but developed to fit the specific requirements of the City of Toronto. Table 6 lists developed parameters:

Table 6. List of TEMOA-TO economic policy constraints

Dimension	Description
CostEmissions	Sets a price on carbon by defining a tax rate on GHG emissions. (Unit: k (2016) CA$ / t CO_2e)
SubsidiesInvest	Represents Investment subsidies or taxes on technology. (Unit: k (2016) CA$ / cap)
SubsidiesFixed	Represents Fixed subsidies or taxes on technology. (Unit: k (2016) CA$ / cap)
SubsidiesVariable	Represents Variable subsidies or taxes on technology or energy. (Unit: k (2016) CA$ / act)

Finally, other constraints on technology share and market share are implemented within TEMOA-TO, using group-based constraints. The idea is to define a group using the **group** parameter and then label the technology in this group using the **tech_groups**. Then the **Weight** parameter defines the technology to include in the constraint and the weight associated. Finally, the **Target** defines the value of the constraint.

Table 7. List of TEMOA-TO group constraints

Dimension	Description
MaxGenGroupWeight MaxGenGroupTarget	**Bound technology target** among a user-defined group of technology.
MinGenGroupWeight MinGenGroupTarget	**Bound technology target** among a user-defined group of technology.
MaxShareGroupWeight MaxShareGroupTarget	**Bound technology share** among a user-defined group of technology.
MinShareGroupWeight MinShareGroupTarget	**Bound technology share** among a user-defined group of technology.
MaxInvestShareGroupWeight MaxInvestShareGroupTarget	**Bound market share** among a user-defined group of technology.

1.3 TEMOA-TO database overview

This section documents the architecture by sector to get an understanding of the overall energy and waste system modelled. However, for deeper technology specific documentation please refer to the following resources available in the *documentation* folder of TEMOA-TO:

- The **nomenclature** includes all the technology modelled, their label, and units;
- The **data inventory** documents the source, assumptions, and nature of data in every CSV file;
- The **data visualization** module extracts flow charts from the model data.

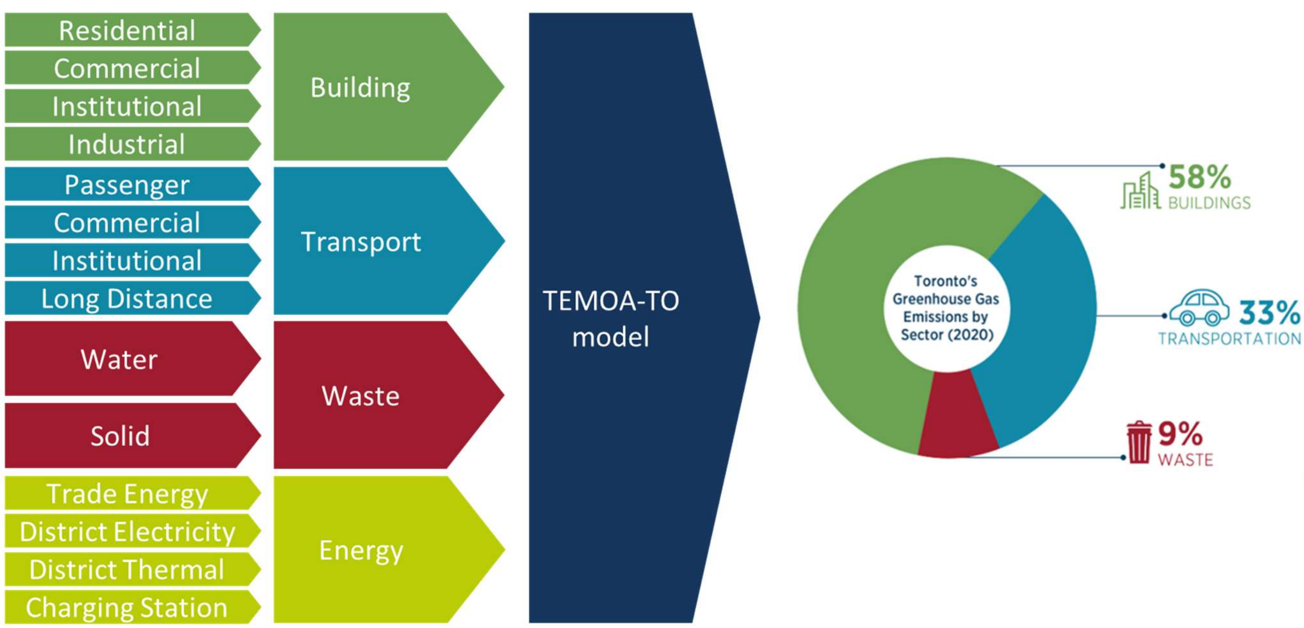
1.3.1. Generalities

The TEMOA-TO model is based on the TEMOA platform and populated with data (

Figure 4). It models the GHG emitting sectors as per the GHG protocol for cities meanwhile:

- Scope 1 and Scope 2 emissions based on the city consumption;
- Scope 3 emissions are partially accounted for, following the GHG protocol for cities;
- The model does not account for life cycle emissions of technologies nor energies (excepting scope 2);
- The model is focused on the main GHG emitting sectors, the agricultural sector and the land-use change are out of the modelling scope.

Figure 4. TEMOA-TO scope and sectors included



1.3.2. Building

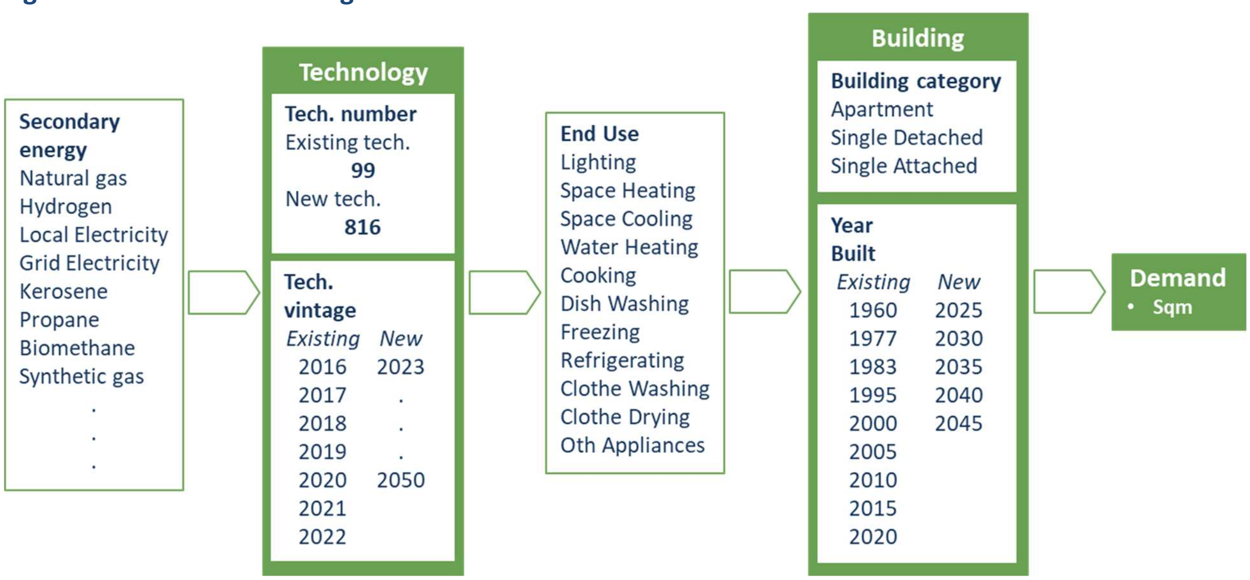
The building sector is split into 4 categories:

- **RESBDG**: Residential Building;
- **COMBDG**: Commercial Building;
- **PUBBDG**: Public Building;
- **INDBDG**: Industrial Building.

For illustration purposes only the residential subsector is described (Figure 5). The demand is the floorspace in square metres. Demand drives the model as an exogenous variable. This demand is split by building categories and year built, from existing to future vintages. Each building category is then converted into end use to satisfy. For example, the corresponding space cooling end use to provide. At the end, existing and new technologies take secondary energy as input, to produce the corresponding amount of end use. The technology choices are optimized by the model.

The arrows in the figure below show the sense of the commodity (energy) flows between technologies (not to be confused with the sense of the optimization: the model is driven by the demand).

Figure 5. Residential building architecture in TEMOA-TO[4]



[4] The lists of years labeled as existing or new change with time. In 2022 when this figure was originally done, 2022 qualified as new for Tech. Vintage. However, in 2026 for example, the years 2022 to 2025 will no longer qualify as new but will move to the existing column. The same applies to Year Built where in 2026, the year 2025 will move to the existing column.

1.3.3. Transportation

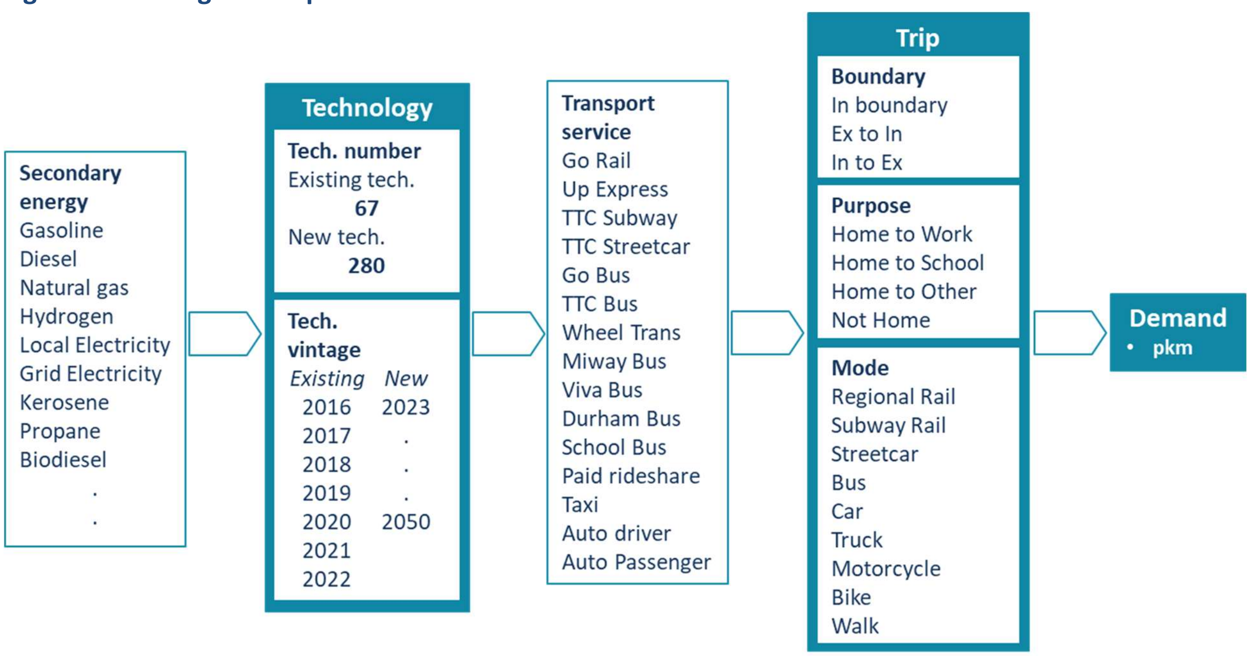
The transportation sector is split into 4 subsectors:

- **PASTRA**: Passenger Transportation;
- **FRETRA**: Freight Transportation (or commercial transportation);
- **PUBTRA**: Public Transportation (public fleet only no transit);
- **LDITRA**: Long Distance Transportation.

The transportation sector is split into 4 categories, for illustration purposes passenger subsectors only is described (Figure 6). The demand is the total distance covered by passengers in a year, the unit used is a technical unit called 'passenger kilometres'. This demand is split by the boundary of travel, meaning where a trip begins and ends, and by purpose of travel. Each trip demand is then converted into a transport service to satisfy, i.e., the required distance travelled by vehicles in a year (the unit used is 'vehicles-kilometres travelled'). At the end, existing and new transportation technologies take secondary energy as input, to produce the corresponding number of vehicles-kilometres travelled. The model optimizes the technology choices.

The arrows in the figure below show the sense of the commodity (energy) flows between technologies (not to be confused with the sense of the optimization: the model is driven by the demand).

Figure 6. Passenger transportation architecture in TEMOA-TO[4]



1.3.4. Waste

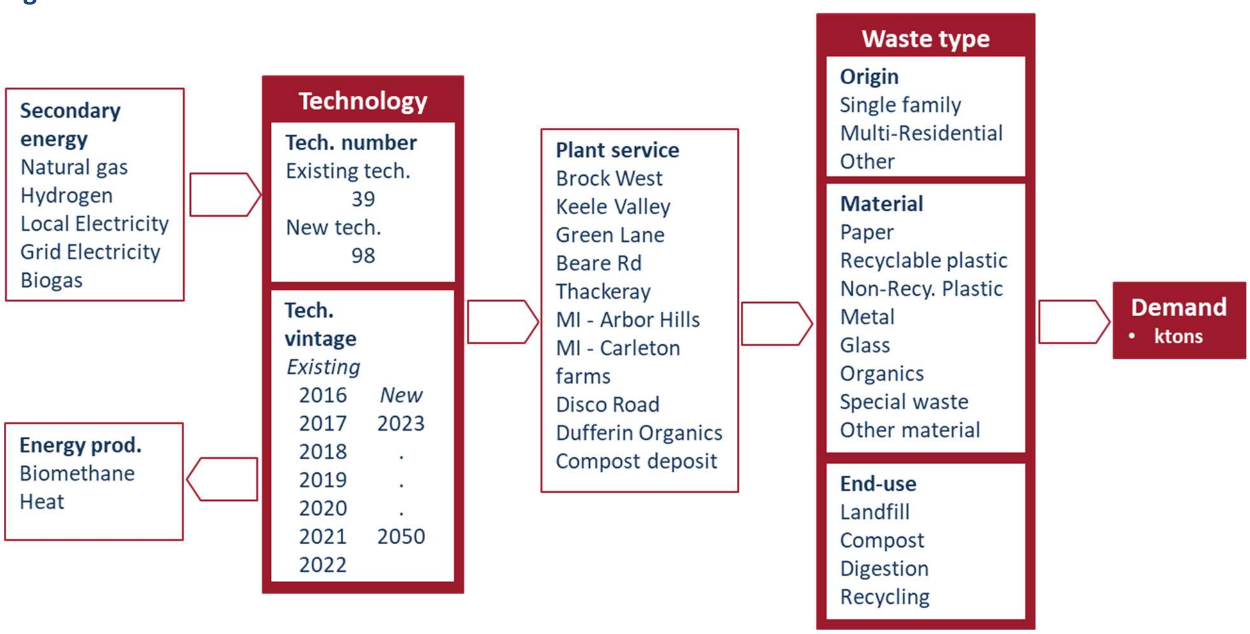
The waste sector is split into 2 subsectors:

- **WATWAS**: Waste Water;
- **SOLWAS**: Solid Waste.

The waste sector is split into 2 categories, for illustration purposes solid waste subsector only is described (Figure 7). The demand is the total tonnage of solid waste material generated within the city boundaries passengers in a year. This demand is split by origins of waste, types of material and end-use types. Each waste demand is then allocated by treatment plant, from landfill depository Green Lane to organic plant type. At the end, existing and new waste management technologies take secondary energy as input, to manage the corresponding amount of waste tonnage. Notes that during decomposition, organic waste is emitting methane, this methane is recovered by the plant and can be used as a secondary energy source by any other sector. The model optimizes the technology choices.

The arrows in the figure below show the sense of the commodity (energy) flows between technologies (not to be confused with the sense of the optimization: the model is driven by the demand).

Figure 7. Solid waste sector architecture in TEMOA-TO[4]



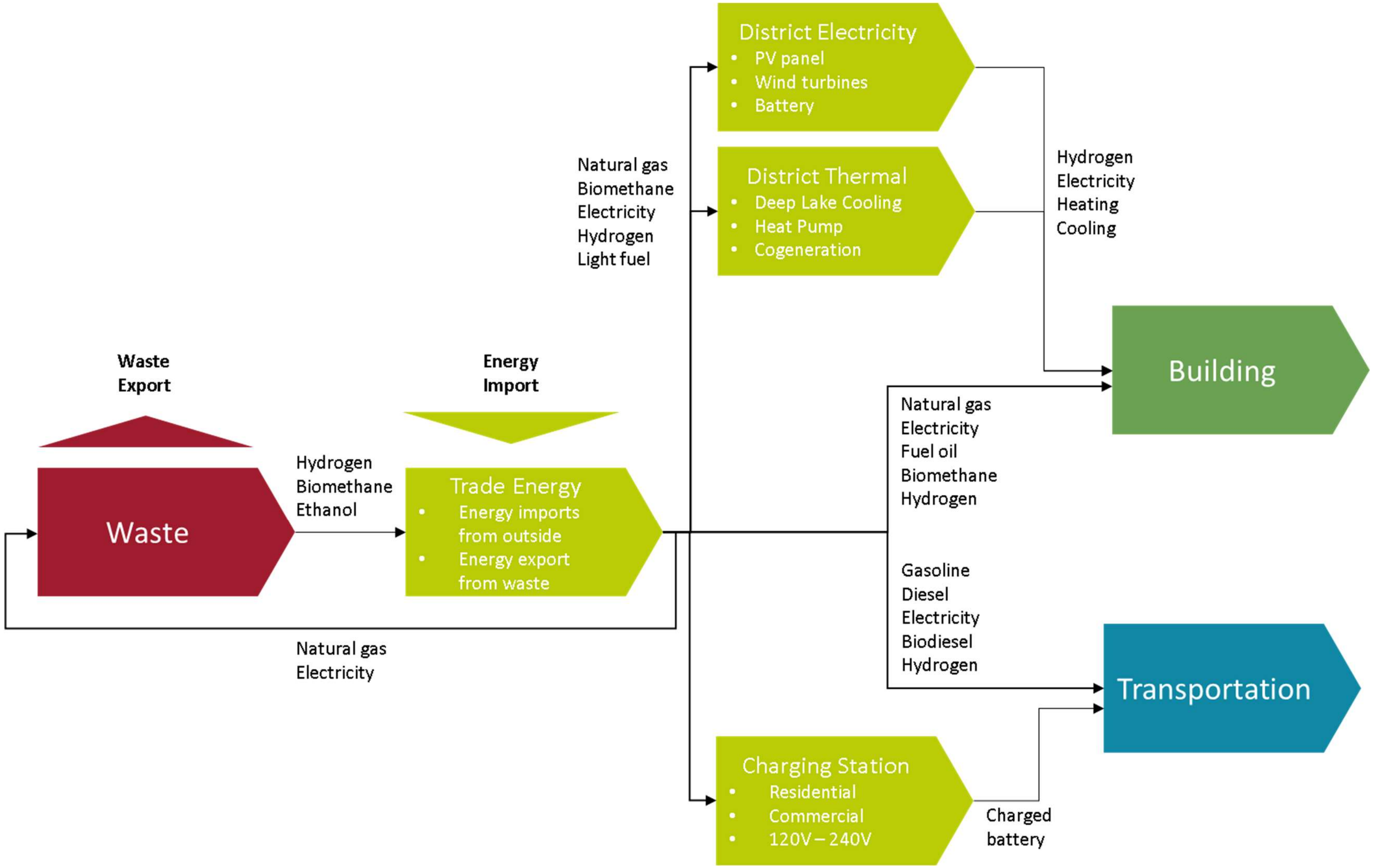
1.3.1. Energy

The energy sector is composed of four distinct modules connected to the three GHG emitting sectors of the model: Transportation, Building and Waste. These energy modules describe the energy supply of the city:

- **TRAENE**: Trade Energy, supply by importing energy from the province, thermal or electrical energy;
- **ELCENE**: Electricity District Energy, supply of decentralized renewable electricity production and storage via solar and wind power coupled with batteries;
- **DISENE**: Thermal District Energy, supply of district heating and cooling, via the production and storage of thermal for district thermal networks, and additional locally generated electricity via controllable combined heat and power (CHP) engines;
- **STAENE**: Electric Charging station, supply for electric vehicles battery charging via commercial and residential charging stations.

Figure 8 represents the technologies listed in the energy modules and the commodity flows between sectors. Note that the flows are not exhaustive, but representative of the energies exchanged.

Figure 8. Energy module architecture in TEMOA-TO



1.4 TEMOA-TO policy modelling

This section illustrates the main constraint types used for policy modelling, as well as additional TEMOA-TO specific constraint types developed within the TEMOA core model. For extensive information on the TransformTO Net-zero Strategy (NZS) and the constraints used to model the policies, refer to ANNEX A.

1.4.1. Constraint development for policy making

In term of policy making several constraints represent better the orientation of market competition between technologies. By comparison with TIMES-MARKAL platform (the NATEM model is based on it) developed by the IEA which includes a large range of constraints, the TEMOA platform includes fewer and less practical constraints.

More specifically, the constraints included by default in the platform are constraints on activity rate or capacity giving a lower or upper bound for a technology. This type of constraint can model most of the technology-oriented policy. However, it is a more time-consuming as it requires to calibrate the constraints. The power of an open-source platform is the possibility for the user to develop additional functionalities on the base core model. ESMIA took advantage of this characteristic by developing new constraint types specific to TEMOA-TO platform. It enhances the overall capabilities of the TEMOA-TO model.

Table 8. Constraint types native and developed for TEMOA-TO.

<table>
<tr><th>Constraint type</th><th>TEMOA native constraints</th><th>Additional constraints developed</th></tr>
<tr><td>Demand shift</td><td>Change Demand or Demand Split (TechInputSplit) parameters with exogenously calculated Demand shift.</td><td>n/a</td></tr>
<tr><td>Subsidies</td><td>Change cost parameter to include subsidy amount.</td><td>Additional subsidy parameters representing:
○ Investment subsidies (e.g., CAPEX Grants)
○ Variable subsidies (e.g., Tax rebates)
○ Fixed subsidies (e.g., Energy affordability program)
○ Emission cost (e.g., Carbon Tax)</td></tr>
<tr><td>Technology share</td><td rowspan="3">Minimum and maximum activity of a technology can be used for all this purposes but require calibration.</td><td>Bound technology share among a user-defined group of technology.</td></tr>
<tr><td>Market share</td><td>Bound investment share by technology among a user-defined group of technology.</td></tr>
<tr><td>Energy share</td><td>Bound energy share among a sector.</td></tr>
<tr><td>Capacity Target</td><td>Minimum or Maximum Target of installed capacity</td><td>n/a</td></tr>
<tr><td>Growth Rate</td><td>The growth rate parameter enables to bound capacity growth by an exponential growth rate factor.</td><td>Additional development on linear maximum growth rate which describes better planned change (e.g., planned retrofit of the building stock)</td></tr>
</table>

These new constraint types helped ESMIA to model the TransformTO NZS in a consistent way. The following sections describe the main policy types and illustrate how to implement it to model the City strategy.

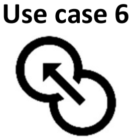
1.4.2. Demand shift

Policy type	Demand shift
Constraints involved	• Demand parameter • Technology Input Split parameter
Description	A demand shift is a policy type used to describe a shift in a system demand implied by a lever out of the modeling scope or with no rational market competition explanation. Such shift often happens in the transportation sector where consumer behavior doesn't rely on economic optimality of their decision. But rather other indicators such as comfort or practicality.
Use case 1 	**Decreased office space per employee.** **Context** The initial projection for commercial building floorspace demand is calculated from macro-economic indicator such as population, GDP and employment. It doesn't rely on the wish of office employee to increase remote work nor potential policies to force partial remote work. **Policy description (from TransformTO)** Reduced office floorspace per employee by a 'mobility factor' of 1.7 (i.e., 20 people per 12 desks), then allocate new commercial floorspace along lines of employment projection. Results in reduced growth in commercial/office floorspace (for new office). **Modelling** To model this specific policy, the methodology is first to estimate the magnitude of the demand shift, here the mobility factor is well defined. Then to apply this mobility factor to the demand parameter for the corresponding scenario.
Use case 2 	**Increased bus lanes and service frequency.** **Context** In optimization model, the choice of cost-optimal does not rely on consumer habit change. Therefore, transportation mode share (personal car, transit, walk) are not concurring but treated as exogenous parameters. **Policy description (from TransformTO)** Convert one lane of traffic to exclusive bus lanes on all arterials. Increase service frequency on all transit routes: bus by 70%, streetcar by 50%, subway off-peak service increased to every 3 mins. **Modelling** To model this policy, the increase in transit frequency is known. A more effective service should bring more costumer. By assuming that the passenger kilometer will increase proportionally to the frequency increase, it results on a demand increase for the defined traffic mode. To model it more precisely, a transit model should be used.

1.4.3. Technology share

Policy type	Technology share
Constraints involved	• Minimum technology group share • Maximum technology group share • Technology Input Split
Description	A technology share constraint is a policy type used to impose a share target of a technology to provide an end-use demand. It defines a projected technology share among end-use (e.g., 100% of passenger vehicles are electric by 2050). To reach its goal, such policy needs to be accompanied with economic incentives to support a technology, additional taxes to decrease attractivity of unwilled technologies or legislative ban of a technology type.
Use case 3 	**City fleet 45% electric by 2030.** **Context** This policy from the City Net-zero Strategy is describing the target to be reached in 2030 in term of electrification of the City fleet. As it is directly under the administration of the City, no additional policy is necessary to reach the target. **Description** Transition 45% of City-owned fleet to low-carbon vehicles by 2030; 65% greenhouse gas reduction by 2030 (from 1990 levels). **Modelling** No specific stock pathway is provided, in this case it will be optimized by the model under the constraint of not being too fast (i.e., it is not technically feasible to change the entire fleet in 2029, even if it could be cost-effective). To let the model, optimize among low-carbon vehicles, a maximum share constraint is imposed on carbon intensive technologies.
Use case 4 	**Renewable natural gas from landfill.** **Context** Most of wastewater plants are already equipped with biodigester as most of landfills are also equipped with biogas capture. However, the installed technology is not the most efficient and often does not exploit the entire potential of the resource. **Description** Greenlane; Keele Valley; All wastewater plants include biodigesters by 2050. **Modelling** When a measure is cost-effective, no additional constraint is needed in an optimization model. Capture biogas from landfill and produce from wastewater is cost-effective and the model will optimize wastewater plants and landfills depository to their maximum potential.

1.4.4. Energy share

Policy type	Energy share
Constraints involved	• Minimum technology group share • Maximum technology group share
Description	An energy share constraint is a policy type used to impose a share target of energy within a subsector. To reach its goal, such policy needs to be accompanied with economic incentives to support an energy, additional taxes to decrease attractivity of unwilled energy or legislative ban of an energy type.
Use case 5 	**Green hydrogen in buildings.** **Context** This policy from the City Net-zero scenario describes the role of hydrogen in natural gas mix. To reach Net-zero, in addition to natural gas phase down in the building sector, hydrogen may also play an important role in decarbonization. Combined with natural gas, it will decrease carbon intensity of the mix. **Description** 10% hydrogen blended into natural gas in residential and commercial buildings by 2050. **Modelling** To model this policy, the easiest way is to impose a 10% energy import share for hydrogen, specifically for residential, commercial, and institutional buildings. Such constraints do not require to be calibrated as it is defined by a relation between variables and not absolute value.
Use case 6 	**Net-zero realistic transition.** **Context** Optimization models are focused on cost-optimal solution, not technical feasibility. It leads to unrealistic solutions where an entire end-use sub-system can shift in a very short period. Such solution is often unfeasible and so unrealistic. **Description** Enable the optimization of a growing share of energy imports (+5% / year). **Modelling** To improve the model inertia energy share constraint are implemented in each sector at the beginning of optimization time, this constraint is progressively relaxed to allow the system to optimize an increasing share of the energy imports.

1.4.5. Tailored constraint

Policy type	Tailored
Constraints involved	• Minimum technology group target • Other
Description	Constraints in the City Net-zero Strategy are not always easily formulated, but rather defined by an equation between variables. Other policies are partially formulated, and modelling assumptions must be decided. Globally any policy which does not fit in one of the previous categories is addressed in this category as tailored constraint.
Use case 7 	**High performance new residential buildings.** **Context** This policy from the City Net-zero scenario describes the building standard for new residential buildings. The Toronto Green Standards includes different Tier categories with selective energy and environmental conditions required. The on-scope standards to be modelled in the project cover the energy efficiency and charging station fields. **Description** All new residential buildings must fulfill: 100% Tier 2 by 2021; 100% Tier 3 by 2022; 100% Tier 4 by 2027. **Modelling** To model this policy Total Energy Use Intensity (TEUI) and Thermal Energy Demand Intensity (TEDI) constraints are to be applied to new building. These constraints define a linear inequality between the floorspace area of a building type and its energy input (thermal or total). The minimum group target constraint is used to model this linear inequality.
Use case 8 	**Increase efficiency of water pumps.** **Context** Water distribution pumps, transfer water from freshwater plants at the Ontario Lake altitude to higher altitude substation then to be delivered to consumers. **Description** Increase efficiency of water distribution pumps. **Modelling** The average altitude increases between Lake Ontario and substation is 80 meters. The efficiency of existing water pumps is estimated to be 50%, which allows an efficiency gain of 30% with technology change. This policy is not implemented with a technology change but through an efficiency change of existing technology. As modelled, it will impact both existing and future years energy consumption.

1.5 TEMOA-TO scenario overview

1.5.1. Scenarios and computation modes

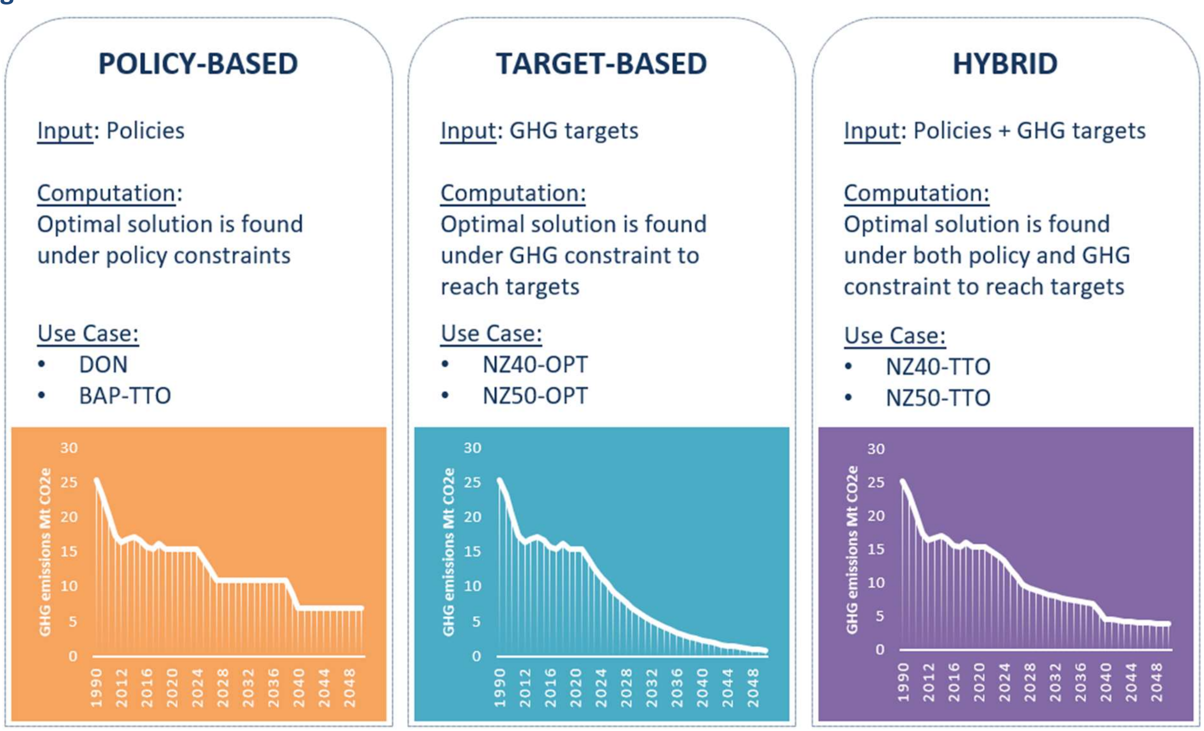
Depending on model's inputs, the model is flexible enough to provide three types of computation approaches (Figure 9).

Policy-based computation enables the user to design policies and assess their impact on costs and GHG. To compute it, policies must be translated into TEMOA language by using native or self designed constraints. The model finds the optimal cost following the policy rules. This use case is particularly useful to compute Do-nothing (DON) and Business-as-planned (BAP) scenarios. It provides multiple scenarios and answers to typical issues of policy makers (e.g., "*How the replacement of nuclear power plant by gas power plant impacts BAP-DON emissions").*

Target-based computation enables the user to assess the cost to reach targets, for example, emission reductions. Input data can be either yearly emission constraints or a single long-term emission target. The model finds the optimal (least cost) path to reach the GHG emissions target or pathway. As the number of constraints is minimized, relative to the policy-based case, the solution provided is often qualified as pure optimization. This methodology provides pure-optimisation net zero scenarios: Net Zero by 2050 scenario (NZ50) and Net Zero by 2040 scenario (NZ40).

Hybrid computation combine both policy-based and target-based inputs. The model finds the optimal cost to reach GHG emissions target under policy constraints. This is the way to better reflect NZ50 and NZ40 by implementing existing and planned policies along with an emission target. It also helps a policy maker to design the most efficient policies to address typical issues (e.g., "*How using 100 per cent biofuel in aviation impacts net zero cost and energy system*").

Figure 9. Use cases of TEMOA-TO model



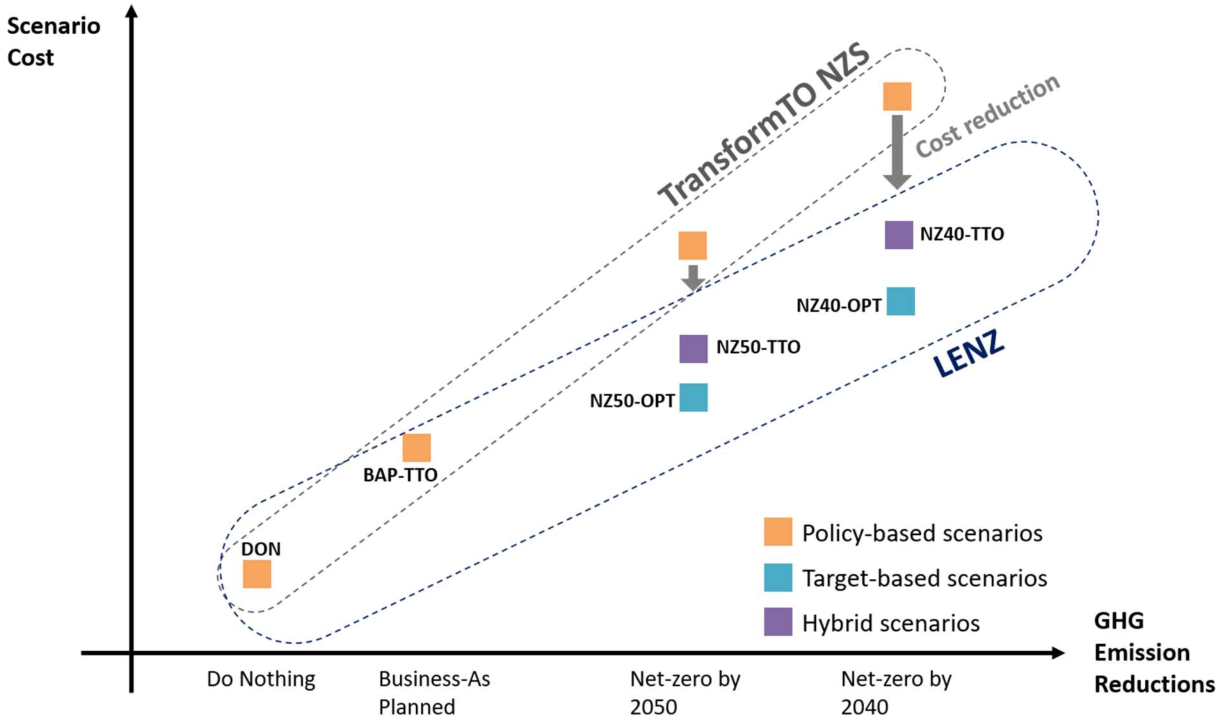
Those three use cases show the difference in nature between optimization and simulation. Optimization can address the three use cases while simulation model can only compute policy-based scenario. The CityInsight initiative leading to the development of TransformTO NZS is a simulation model. It enabled the City to develop a plan to reach its commitment. The present initiative TEMOA-TO enhances the City Net Zero Strategy by proving its robustness, assessing its cost-optimality, and computing milestones to reach policy targets. This enhancement is achieved by providing six main scenarios, complementary to TransformTO scenarios.

1. **DON**: A **Do Nothing** scenario (Business As Usual scenario (BAU) in the NZS) to compare and make sure the GHG projections were aligned with the Do-Nothing scenario of the TransformTO NZS. This scenario represents what would happen if the current energy and waste system is preserved until 2050.
2. **BAP-TTO**: A **Business-as-planned** scenario to assess the impact of the TransformTO NZS policies on GHG emissions (policy-based scenario). It is useful to assess the impact of the current policies on GHG emissions combined with the natural evolution of the system resulting from market competition between technologies and energy costs.
3. **NZ50-TTO**: A hybrid scenario, representing how the City may achieve **net zero GHG by 2050** while considering the policies and targets of the NZ50 scenario from the TransformTO NZS.
4. **NZ50-OPT**: A target based or pure-optimal scenario, representing the cost-optimal pathway to reach **net zero GHG by 2050**.
5. **NZ40-TTO**: A hybrid scenario, representing how the City may achieve **net zero GHG by 2040** while considering the policies and targets of the NZ40 scenario from the TransformTO NZS.
6. **NZ40-OPT**: A target based or pure-optimal scenario, representing the cost-optimal pathway to reach **net zero GHG by 2040**.

LENZ will generate cost optimal pathways for both types of net zero scenarios. However, the NZ50-TTO and NZ40-TTO scenarios are modelled using a hybrid approach where both GHG targets and policy constraints are applied, while the NZ50-OPT and NZ40-OPT scenarios are modelled using a target-based approach where only GHG targets are considered. Consequently, there is more flexibility to explore cost optimal solutions in the OPT scenarios. By comparing results from the TTO and OPT versions of each scenario, areas where the solutions diverge can be investigated to formulate recommendations for new policy design, or new sector policy targets.

Initial analysis indicates that cost reductions can be achieved in comparison with the findings from the TransformTO NZS (Figure 10).

Figure 10. Cost-optimality comparison of TransformTO vs TEMOA-TO scenarios



1.5.2. Hybrid scenarios

Do Nothing scenario

The DON scenario is the reference scenario that was created to reflect what would happen if the City took no additional action to address climate change. It is the equivalent of the BAU scenario from the NZS. It includes anticipated population growth and current technology usage, as well as the impact of climate change on heating and cooling requirements. Please note that it does not represent the most likely energy and waste system to appear under no policy regulation and pure market competition. It represents better the evolution of the energy and waste system without any major disruption between reference year and final year. Efficiency gains could occur if they are cost-effective, but no major energy supply switch.

Simply allowing the base model to optimize without imposing any additional constraints is insufficient for the DON scenario. In this case, it would still invest in the most competitive technology at each time slice, which could create energy and waste system disruption. Therefore, additional assumptions are required to model this scenario. Table 9 shows the main assumption used for DON computation, for more information on the policies for this scenario please refer to the Policy inventory in the TEMOA-TO directory.

Table 9. Main policies for Do Nothing scenario

Sector	Policy
District electricity	District electricity is banned from the City investments
District thermal	District thermal energy is banned from the City investments, existing networks are preserved.
Waste	Energy produced from waste treatment (landfill depository, wastewater treatment, organic plant) is not exported to other sectors but uncollected or collected and flared.
Trade energy	Energy mix import from outside Toronto remains constant between periods in each building and transportation subsector: Passenger transportation, Residential building, Industrial building, etc.

Business-As-Planned scenario

The BAP-TTO represents the most likely energy and waste system to appear under the City approved policies and market competition. The City policies are modelled based on the BAP scenario from the TransformTO NZS. Market competition is natively modelled as TEMOA-TO is an optimization model, allowing cost-effective investment, efficiency gain and fuel switch.

The complete list of the City policies is provided as ANNEX A. Table 10 summarizes the main assumptions extracted from the City strategy to model Business-As-Planned scenario.

Table 10. Main policies for Business-As-Planned scenario

Sector	Policy
Building	Scope: Residential, Commercial, Institutional ○ After 2031, new building to comply with Toronto Green Standards (V4); ○ Around 20 per cent of existing buildings to be retrofitted by 2050 with 15 per cent electricity and 35 per cent thermal gains.
Transportation	○ Urban transit to be electrified by 2030; ○ Public, passenger and commercial fleets to be electrified by 2050.
Waste	○ Produce Renewable Natural gas from waste treatment; ○ Increase diversion rate to 70 per cent in 2025.
Energy	○ Install planned district energy.

This scenario is not perfectly comparable with CityInsight Business-As-Planned scenario. The difference led to the fact that in CityInsight policy making is the only driver to GHG emissions and no unplanned change happens in the system. In TEMOA on the other hand, unplanned disruptions happen according to cost optimality.

Net Zero by 2050 scenario

The NZ50-TTO represents an energy and waste system compliant with the City Net Zero Strategy to provide demand with a minimum final amount of GHG emissions in 2050. This final amount of GHG emissions is related to the grid electricity consumed within the city boundaries. Decarbonizing grid electricity is out of the City's jurisdiction. However, it is still accounted in its scope 2 GHG emissions according to the GHG protocol for cities[5].

This scenario includes every policy previously designed for BAP-TTO scenario, and additional NZ50-TTO policies from the NZ50 scenario from the TransformTO NZS. The complete list of TransformTO policies is provided as ANNEX A. Table 11 summarizes the main assumptions extracted from the City strategy to model net zero by 2050 scenario.

[5] Greenhouse Gas Protocol (2021). GHG Protocol for Cities: An Accounting and Reporting Standard for Cities. Online (Accessed in February 2023): https://ghgprotocol.org/greenhouse-gas-protocol-accounting-reporting-standard-cities

Table 11. Main policies for net zero by 2050 scenario

Sector	Policy
Building	Scope: Residential, Commercial, Institutional o In 2021, 2022, 2023, new building to comply with Toronto Green Standards Tier1, Tier 2, Tier 3; o 100 per cent of existing building stock to be retrofitted by 2050 with 15 per cent electricity and 75 per cent thermal gain; o Heat pump to provide heat and water heating for 100 per cent of consumers.
Transportation	o Demand shift from personal vehicle transportation to bikes and transit; o 100 per cent of Public, passenger and commercial fleets electrified by 2050; o Use biofuel to decarbonize remaining end-uses (air, rail).
Waste	o Increase diversion rate from 70 per cent in 2025 to 95 per cent in 2050.
Energy	o Use of biofuels in district energy facilities; o Install 2000 MW of stationary battery, 200 MW of wind turbines and 3675 MW of solar panels.

Net Zero by 2040 scenario

Similarly to NZ50-TTO, the NZ40-TTO represents the energy and waste system compliant with the City Net Zero Strategy to provide demand with a minimum final amount of GHG emissions in 2040.

This scenario includes every policy previously designed for BAP-TTO and NZ50-TTO scenarios, and additional policies from the NZ40 scenario from TransformTO NZS. The complete list of the City policies is provided as ANNEX A. Table 12 summarizes the main assumptions extracted from the City strategy to model NZ40-TTO scenario.

Table 12. Main policies for Net Zero by 2040 scenario

Sector	Policy
Building	Scope: Residential, Commercial, Institutional o In 2021, 2022, 2023, new building to comply with Toronto Green Standards Tier1, Tier 2, Tier 3; o 100 per cent of existing building stock to be retrofitted by 2050 with 15 per cent electricity and 75 per cent thermal gain; o Heat pump to provide heat and water heating for 100 per cent of consumers.
Transportation	o Demand shift from personal vehicle transportation to bikes and transit; o 100 per cent of Public, passenger and commercial fleets electrified by 2050; o Use biofuel to decarbonize remaining end-uses (air, rail).
Waste	o Increase diversion rate from 70 per cent in 2025 to 95 per cent in 2050.
Energy	o Use of biofuels in district energy facilities; o Install 2000 MW of stationary battery, 200 MW of wind turbines and 3675 MW of solar panels.

1.5.3. Pure-optimization scenarios

Pure optimization is not fuelled by policies but driven by emission target or pathway. It provides insightful data on the cost-optimal way to reach a target or follow a pathway. The main characteristics of target and pathway-based optimization is summarized in Table 13 and detailed below it.

Table 13. Characteristics of target and pathway-based optimization

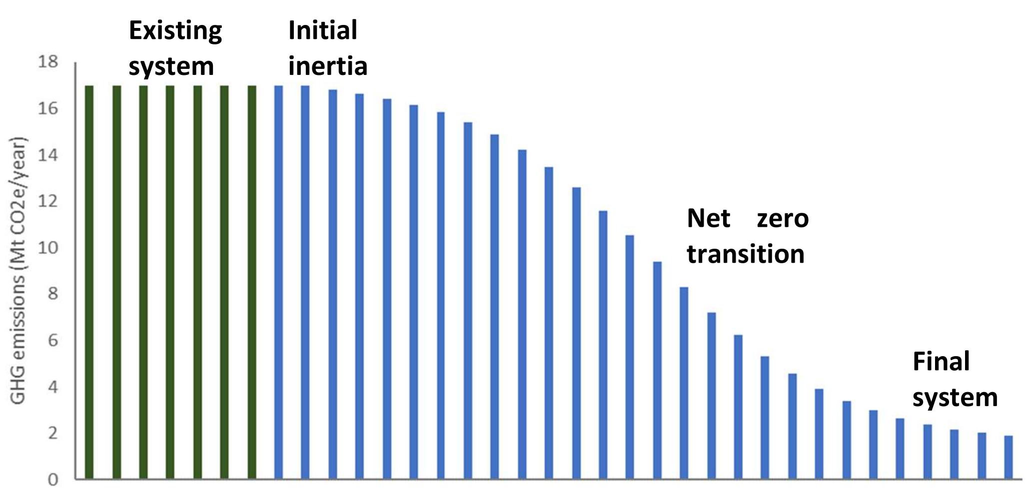
Criteria	Target based	Pathway based
Optimality	Most optimal	Constrained optimality
Feasibility	High speed transition rate	User inputs transition rate
Variability	Possibility to implement milestones before final target	Multiple profiles curves

Target based optimization is the most cost-effective way to implement net zero scenarios. By implementing the target only, every cost is optimized to reach the objective.

Pathway based optimization is the most realistic way to implement net zero scenarios, no feasible transition scenario happens in years but rather in decades. Such pathway is composed of 4 phases (see Figure 11):

- Phase 1: **Existing system** where the system GHG emissions are known and calibrated, the value of the gauge should be the maximum GHG emission value of modelled existing years.
- Phase 2: **Initial inertia,** energy and waste system has a lot of inertia from both supply and demand. This second phase allows emissions to stay below the maximum level of existing years.
- Phase 3: **Net zero transition** switching from a carbon-based energy and waste system to a more resilient and sustainable system based on carbon-free energy is the net zero transition, it can be of diverse form linear transition to inverse S curve The emissions must decrease at least at the S curve rate.
- Phase 4: **Final system** at this stage the energy and waste system is fully optimized and is constrained to keep its emission under the net zero emission target.

Figure 11. Typical GHG emission pathway for pure optimization

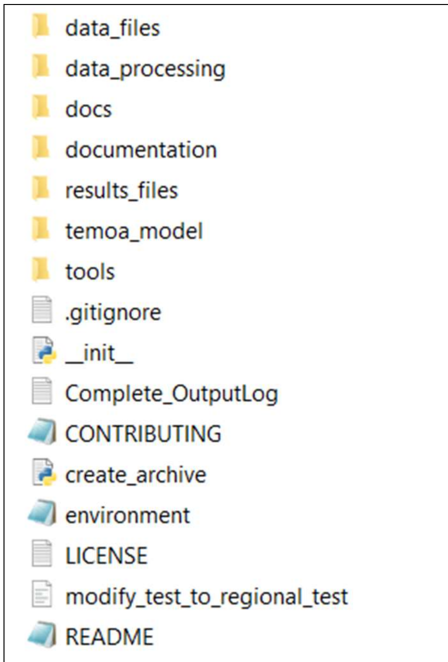


1.6 How to use TEMOA-TO ?

This section shares basic knowledge on the methodology to configure and run scenario from TEMOA-TO as well as the methodology to export results.

1.6.1. The overall project

Figure 12. TEMOA-TO project architecture



data_files include all the CSV and SQL input data of the model. *data_processing* includes modules for output data processing and input data visualization. *documentation* includes the specific documentation related to TEMOA-TO, more specifically it includes commodity and technology nomenclature, modelled policy inventory, and input data inventory. *result_files* include TEMOA-TO a standardized dashboard for solution visualization as well as specific tools to extract output CSV files from SQLITE output files. *temoa_model* contains TEMOA core model (i.e., the Python code defining the energy optimization model) *tools* include sensibility analysis tools such as monte-carlo or stochastics, these functionalities are not tested for the TEMOA-TO model.

1.6.2. Understand input data

This section refers to both data architecture in the *TEMOA-TO/data_files/import_data* folder. For a deeper understanding of the input parameters & constraints please refer to the documentation folder within the TEMOA-TO model.

Overview of data architecture

The TEMOA platform does not natively include an importation module, this module is specifically developed for TEMOA-TO and may require to be modified to be compatible with another TEMOA-based project. The main function of this module is to enable the user to write and modify the model inputs in excel compatible files (CSV files) instead of dealing with input SQL file, less user friendly.

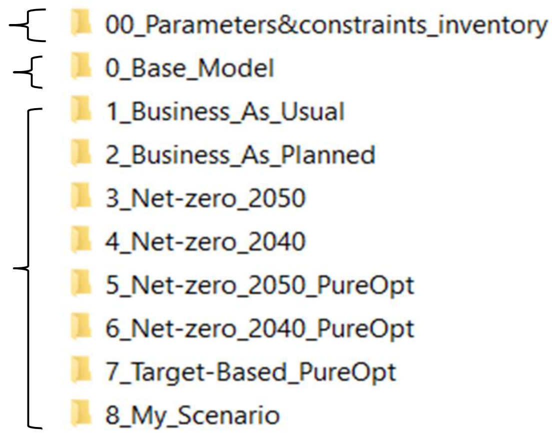
Figure 13. Level 1 in *import_data* folder

Parameters & Constraints CSV templates

Base model folder including data representing the system, demand, existing and new technologies.

Scenario folders including scenarios specific data, it includes 2 types of data to:

- Overwrite of *0_Base_Model* parameters (e.g., Demand change);
- Add policy-based constraints (e.g., Energy ban).



Base model architecture

The *0_Base_Model* folder includes all the data representing the base model (i.e., Existing system, New technology, Demand), every run requires importing those data. More specifically it includes the main simulation parameters in *0_Parameters* and the sectorial data in the other folders and sub-folders as shown in Figure 14.

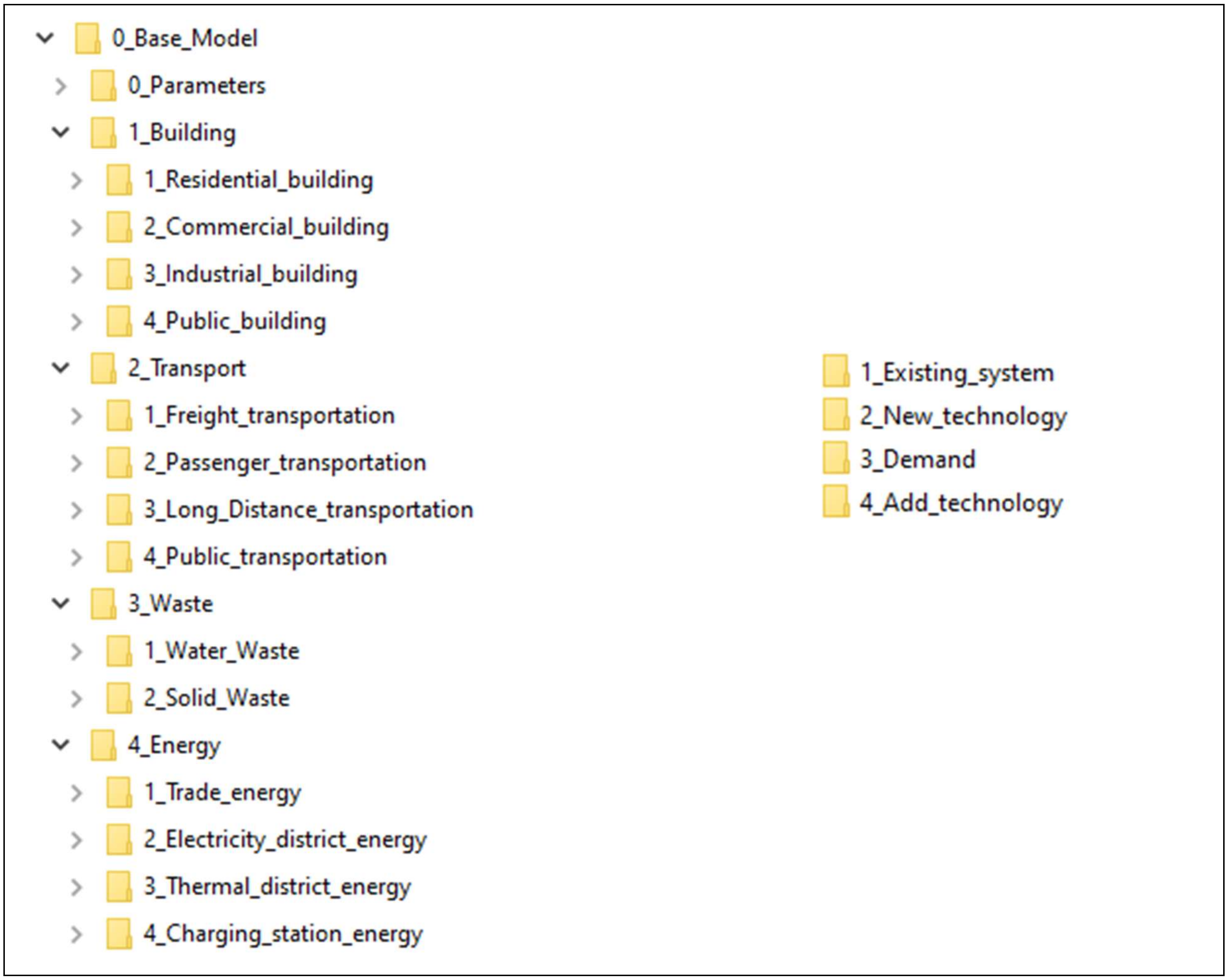
For more information on the scope of each sub-sector please refers to section 1.3. Every subsector folder includes the subfolders shown in Figure 14.

- *1_Existing_system* represents the energy and waste system technology in 2016, the base year;
- *2_New_technology* relates to new technologies which can be invested in by the model in the future years;
- 3_*Demand* relates to architecture technologies, exogenous demand for subsectors and their subdivision by end-use;
- 4_*Add_technology* enables to add new sectorial technologies. The best practice is to not directly add technology in the *2_New_technology* folder but to add them in *4_Add_technology* (see 1.7.2).

In cases, note that one or multiple folders are missing, the main cause for this includes:

- Missing *1_Existing_system*, means historical year is not mapped or considered negligible (e.g., historical local electricity production is not mapped);
- Missing *2_New_technology,* means no technological change happened in the period modelled *(e.g.,* trade energy subsector does not include new technology for imports);
- Missing *3_Demand*, means the subsector does not have an exogenous demand (e.g., energy subsectors have no direct energy demand, energy demand depends on other sectors technology choice);
- Missing *4_Add_technology,* if this folder is missing, the user can create it if needed.

Figure 14. Level 2, 3 and 4 of *0_Base_Model* folder



Each level 4 subfolder includes an *Input* and an *Output* folder:

- *Input* folder includes all the CSV input files (please refer to sections 1.2.3 to 1.2.5 for the descriptions of those input files);
- *Output* folder includes intermediate SQL files generated by the *Generate_SQL.py* script;
- *Calibration* folder, typically included in the new technology folder of transportation and building sectors, more information is provided on calibration in section 1.7.4.

Scenario folder architecture

Additionally, the project also includes scenario folders. These folders aim at adding scenario specific constraints or parameter modification.

Figure 15. Level 2 of *Scenario* folder

Those folders use the same architecture as in the *Base_model* folder, and its purpose is to **overwrite** data from the *Base_model* folder. Note that if data are not in the *Base_model*, it will import this additional chunk of data.

- 1_Building
- 2_Transport
- 3_Waste
- 4_Energy

Those folders include scenario specific; they are classified by sector. The Emissions Limit policy is separated as it impacts all sectors.

- 5_Policy
  - 1_Building
  - 2_Transport
  - 3_Waste
  - 4_Energy
  - 5_EmissionLimit

Each sector of the *5_Policy* includes a list of folders with an ID name. This ID name corresponds to the policy ID as per policy inventory in the *documentation* folder (i.e., Figure 12).

Each policy folder includes the following files:

- *Input* folder includes all the CSV input files;
- *Output* folder includes intermediate SQL files generated by the *Generate_SQL.py* script;
- *Policy file* describes the calculation methodology and assumptions to model the policy.

1.6.3. Configure a scenario

Choose a solver according to the problem size of and hardware configuration

Due to the size of the problem, it is advised to solve the model using a powerful optimizer and a hardware with sufficient configuration.

In term of solver, the CPLEX optimizer developed by IBM is the preferred solver for the project, but other solvers may be used. More specifically GUROBI, COIN-CBC, and GLPK solvers. Using Gurobi may not increase significantly the solving time compared to CPLEX, however using open-source solvers as GLPK and COIN-CBC may significantly increase the solving time. Open-source solvers may also be used, prefer COIN-CBC which offers higher performances. For CPLEX users, note that the default CPLEX settings are tuned to improve solving time. The current algorithm used is the Barrier (Interior Point) without Cross over. In term of hardware configuration, the minimal configuration to run the project would be an I5 CPU with 8 GB of RAM, but 16 GB of RAM is a must. To mitigate the risk of impossibility to run the model with your personal computer, two drivers may be used, decrease the number of sectors, or decrease the temporal resolution.

1. **<u>Decrease the sectorial scope</u>** - *data_files /import_adress*

The *import_adress.txt* file, let the user to choose a set of sectors to import instead of importing the whole Toronto model. Running by sub-sector, requires adapting some constraints (e.g., Emissions Limit constraint) and could lead to slightly different solutions. However, it may lead to significant cut in solving time. Table 14, show indicative capacity for each solver to run the entire model or sub models.

Table 14. Indicative capacity of solvers to run sub-models

Sectors/Solver	Size of the subsector (+ - +++)	CPLEX (PR)	GUROBI (PR)	COIN-CBC (OS)	GLPK (OS)
Entire model	+++	✓	✓		
Waste	+	✓	✓	✓	✓
Solid	+	✓	✓	✓	✓
Water	+	✓	✓	✓	✓
Building	+++	✓	✓		
Residential	+++	✓	✓	✓	
Commercial	+++	✓	✓	✓	
Public	++	✓	✓	✓	
Industrial	+	✓	✓	✓	✓
Transportation	++	✓	✓		
Passenger	++	✓	✓	✓	✓
Freight	++	✓	✓	✓	✓
Public	+	✓	✓	✓	✓
Long Distance	+	✓	✓	✓	✓

A few points to note when running the model by sector:

- **Keep importing energy production sectors**: The energy sector should always be imported in a by sector approach as it fuels the other sectors with energy.
- **The GHG emission baseline will be impacted**: running by sector does not mean optimizing a sector in the same model. It actually reduces the scope of the model to one sector, and report GHG emissions for the sector only. Consequently, the GHG emission target should be adjusted from a global target to a by sector target.
- **The limited resources allocation will be impacted**: limited resource allocation such as biomass or biomethane may be significantly impacted by limiting the sector scope. To mitigate this risk constraining resource availability by sector may be the key.
- **By sector approach may be useful for testing purpose**: when testing a new constraint or policy, cutting on the sector definition may be an interesting way to reduce solving time.
- **By sector approach generates unique insights**: Some insights from TEMOA such as the marginal carbon abatement cost cannot be disaggregated by sector in a standard run. Running by sector may allow to generate sector specific GHG emissions abatement cost curve.

2. **<u>Decrease the temporal resolution</u> -** *data_files/import_data/0_Base_Model/0_Parameters/Input/time_periods*

The *time_periods.csv* file in the *0_Parameter* folder, includes the period definition of the run. As the model is built annually it is theoretically possible to run the model annually. However, it would require tremendous calculation power to be solved in a realistic time. By default, we use the **Advised resolution** as per Table 15, which provide a good balance between solving time and period resolution. To decrease by half the solving time, Lower resolution may be used.

Table 15. Period configuration and indicative solving time[6]

Configuration	Existing years (e)	Annual (f)	Other years (f)	Indicative solving time
Higher resolution	Do not modify	2016 - 2030	2035;2040;2045;2050;2051	750 min
Advised resolution		2016 - 2025	2030;2035;2040;2045;2050;2051	80 min
Lower resolution		2016 - 2025	2030;2040;2050;2051	40 min

Changing the period configuration does not significantly impact the projected energy and waste system. However, the resulting cost especially the Total net present cost could be different. As an advice, the cost of the solution should not be compared between runs using different period definition.

Configure the importation process

The importation process is ruled by the *Generate_SQL.py* script in the *data_files* folder. The script import data from the *Base_model* and the selected *Scenario* according to *Import_adress.txt*.

Import_adress.txt file is a text file and can be opened with any notepad. This file rules the importation process. To import an address, the desired line should be uncommented by deleting # at the very beginning of addresses. It is composed of 4 sections (Figure 16 and Figure 17):

- **Export_name**, to choose the name of the SQL file created by *Generate_SQL*.py
- **Scenario**, to choose the scenario to import. *Base_model* should always be imported. Note that the importation code cannot deal with multiple *Scenario* importation.

[6] The indicative solving time is obtained by solving the Do Nothing scenario with the CPLEX solver using the following hardware:

Processor	Intel(R) Core(TM) i7-10750H CPU @ 2.60GHz 2.59 GHz
Installed RAM	32.0 GB

Figure 16. Export_name and Scenario in *import_adress.txt*

```
                  ####################################################################
                  #---------------------- LIST OF ADRESS TO IMPORT ----------------------
                  ####################################################################

Export name     { //Export_name//
                  NZ50-opt

                  #-----------------------------------------------------------------
                  #----------------------------- SCENARIO----------------------------
                  #-----------------------------------------------------------------

Base model      { import_data/0_Base_Model/
                  #import_data/1_Business_As_Usual/
                  #import_data/2_Business_As_Planned/
                  #import_data/3_Net-zero_2050/
                  #import_data/4_Net-zero_2040/
Scenario        { import_data/5_Net-zero_2050_PureOpt/
                  #import_data/6_Net-zero_2040_PureOpt/
                  #import_data/7_Target-Based_PureOpt/
                  #import_data/8_My_Scenario/
```

- **Sector,** to choose the sectors to import. All the uncommented sectors from *Import_adress.txt* will be imported from *Base_model* and the chosen *scenario*. Note that a subsector cannot be imported partially, the entire subsectors should be imported. Additionally, the energy sub-sector should always be imported, especially the trade energy module which defines energy imports.
- **Policy,** to choose the policies to import. Usually, this section should stay uncommented, but it could be useful to comment it partially for debugging purposes (1.8.3).

Figure 17. Sector and Policy imports in *import_adress.txt*

```
#-------------------------------------------------------------
#------------------------------SECTORS-----------------
#-------------------------------------------------------------

#---------------------------- PARAMETERS--------------

0_Parameters/

#------------------------------ BUILDING -------------

#-------------------- Residential Building - RESBDG
1_Building/1_Residential_building/1_Existing_system/
1_Building/1_Residential_building/2_New_technology/
1_Building/1_Residential_building/3_Demand/
1_Building/1_Residential_building/4_Add_technology/

#-------------------- Commercial Building - COMBDG
1_Building/2_Commercial_building/1_Existing_system/
1_Building/2_Commercial_building/2_New_technology/
1_Building/2_Commercial_building/3_Demand/
1_Building/2_Commercial_building/4_Add_technology/
```

```
#-------------------------------------------------------------
#------------------------------ POLICY-------------
#-------------------------------------------------------------

#--------------------------- EmissionLimit----------

5_Policy/5_EmissionLimit/

#--------------------------Business-As-Usual--------

5_Policy/4_Energy/BAU-ENE-1/

#-------------------------Business As Planned-------

#------ Building
5_Policy/1_Building/BAP-BDG-1/
5_Policy/1_Building/BAP-BDG-2/
5_Policy/1_Building/BAP-BDG-3/
5_Policy/1_Building/BAP-BDG-4/
5_Policy/1_Building/BAP-BDG-5/
5_Policy/1_Building/BAP-BDG-6/
```

CSV input data of the scenario (see 1.6.2) must be regrouped into an SQL database. This is done by the *Generate_SQL.py* script that proceed as such:

1. **Duplication** of the *raw.sql*, make sure to keep this file;
2. **Conversion** of CSV files of *Input* folders to intermediate SQL files in the *Output* folders;
3. **Consolidation** of SQL file by importing every intermediate SQL file;
4. **Deletion** of data duplicates.

The SQL database is then converted to an SQLITE database to be read as input and output of TEMOA-TO (see instruction to do so in section 1.6.4).

Configure configuration file

The configuration file located in *temoa_model/config_sample* contains TEMOA configuration parameters for the run and should be updated according to the scenario name.

Figure 18. Configuration file for TEMOA run

First, indicate the name of the input & output SQLITE files. A good practice is to use the same file for **input** and **output** and to keep the same name as in *import_adress.txt* file (see Figure 16).

```
# Input File (Mandatory)
# Input can be a .sqlite or .dat file
# Both relative path and absolute path are accepted
--input=data_files/BAP.sqlite

# Output File (Mandatory)
# The output file must be a existing .sqlite file
--output=data_files/BAP.sqlite
```

Then, enter the name of the **scenario**, a good practice is to use the same name as the export name.

```
# Scenario Name (Mandatory)
# This scenario name is used to store results within the output .sqlite file
--scenario=BAP
# Path to folder containing input dataset (Mandatory)
# This is the location where database files reside
--path_to_data=data_files

# Solve Myopically (Optional)
# Allows user to solve one model time period at a time, sequentially
# Default operation is "perfect foresight"
#--myopic
#--myopic_periods=2
#--keep_myopic_databases
```

To keep dual values, comment or uncomment **saveDUALS** line.

```
# Report Duals (Optional)
# Store Duals results in the output .sqlite file
--saveDUALS
```

To export the main results in an excel file, uncomment **saveEXCEL** line.

```
# Spreadsheet Output (Optional)
# Direct model output to a spreadsheet
# Scenario name specified above is used to name the spreadsheet
--saveEXCEL
```

To export the log files, uncomment **saveTEXTFILE** line.

```
# Save the log file output (Optional)
# This is the same output provided to the shell
--saveTEXTFILE
```

Finally, select the **solver**, multiple open-source (COIN-CBC, GLPK) or private (CPLEX, GUROBI) can be used.

```
# Solver-related arguments (Optional)
#--neos                    # Optional, specify if you want to use NEOS
--solver=cplex             # Optional, indicate the solver cplex, gurobi,
--keep_pyomo_lp_file       # Optional, generate Pyomo-compatible LP file
```

1.6.4. Run TEMOA-TO

This tutorial addresses how to run a scenario, it is specific for Windows users as the model is untested on Mac OS nor Linux.

Install and Set TEMOA-TO

Download the code folder, unzip it, and place the folder under the C drive.

Open the *environment.yml* file with a text editor. To check if the environment is correctly created, open an Anaconda Prompt, and enter each line from Figure 19 followed by enter. Note that the prompt after # are comments and not comments.

Figure 19. Creation of the TEMOA environment

Anaconda Prompt

```
cd [path to TEMOA directory]

conda env create -f environment.yml #Creation of the environment

conda env list #Display the list of environments
```

If the environment is correctly installed, a line confirming the installation of temoa-py3 environment, and its location may appear on the anaconda prompt:

Figure 20. Environment installation check

```
(base) C:\Users\esmia>conda env list
# conda environments:
#
base                  *  C:\Users\esmia\anaconda3
linking_tool             C:\Users\esmia\anaconda3\envs\linking_tool
silver_env               C:\Users\esmia\anaconda3\envs\silver_env
temoa-py3                C:\Users\esmia\anaconda3\envs\temoa-py3
```

Open an Anaconda Prompt and enter the commands as per Figure 21 to activate the virtual environment.

Figure 21. Activate TEMOA environment

Anaconda Prompt

```
conda activate temoa-py3 #Activate the environment
```

Configure the scenario

Make to follow the guidelines in 1.6.3 to configure the scenario:

- Configure the *import_adress.txt* file in the *data_files* folder;
- Configure the *config_sample.txt* file in the *temoa_model f*older;
- Make sure to have **previously deleted *[file name].sqlite*** in *data_files* folder.

To generate the SQLITE input file, open an Anaconda Prompt and enter the command from Figure 22 followed by enter. Note that the prompt after # are comments and not commands.

Figure 22. Generate SQL and convert into SQLITE

Anaconda Prompt

```
cd [path to data_files folder in TEMOA directory]

Python Generate_SQL.py #Generation of SQL file

sqlite3 [file name].sqlite < [file_name].sql #Convertion of SQL to SQLITE
```

Run the model

To run the model, open an Anaconda Prompt and enter the command from Figure 23 followed by enter. Note that the prompt after # are comments and not commands. The [path to TEMOA directory] specified in the command prompt is the main directory that contains the folder "temoa_model", and not the folder "temoa_model" itself (for example, the path is c:\LENZ \TEMOA-TO and not c:\LENZ \TEMOA-TO\temoa_model).

Figure 23. Run TEMOA model

Anaconda Prompt

```
conda activate temoa-py3 #Activation of the environment

cd [path to TEMOA directory]

Python temoa_model/ --config=temoa_model/config_sample #Run the model
```

After the last line to run the model, press enter a second time to execute CPLEX which will be displayed after some time. If you do not hit enter a second time, the run will be idle and will not proceed until you hit enter. If facing a CPLEX error, please refer to the comprehensive installation guide in ANNEX C.

The output files of the run will be located in *data_files* folder, in a new folder with the name of the scenario, and in the SQLITE database used. Section 1.6.5 provided instructions to visualize results of the run.

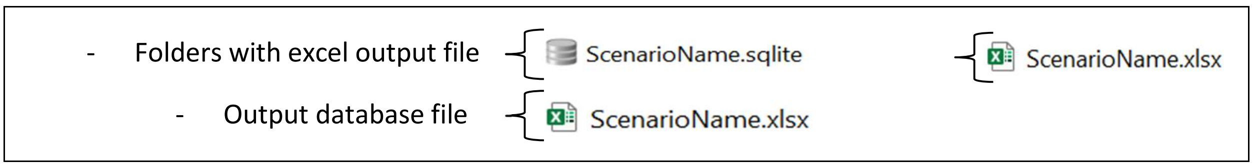
1.6.5. Export and visualize the results

To visualize the outputs from the run, two options are available:

- **a dashboard** showing macro indicators (e.g., cost, energy mix, GHG emissions);
- **the result files generator** for more extensive results.

To use the visualization tools refer to the *data_files* folder, including: the output SQLITE database, and the folder including an EXCEL output file as per Figure 24. This EXCEL file contains capacity, activity, emission, and cost of all technology through years modelled. The major difficulty lies in the fact that technologies are named by their identification label. To have the description corresponding to each identification label, use the *Nomenclature* in the *documentation* folder.

Figure 24. Structure of TEMOA's outputs



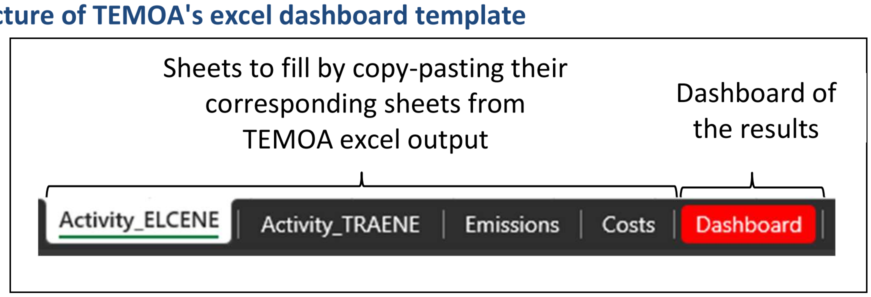
Results dashboard

From the output excel file of TEMOA (presented in Figure 24), use the template *Overview_Dashboard.xlsx* file in *results_files* to visualize the results. Copy the corresponding sheets ('Acticity_ELCENE', 'Activity_TRAENE', 'Emissions', and 'Costs') from the excel output and paste it in the Dashboard workbook (Figure 25).

In the Dashboard main sheet, graphs are plotted through years modelled from those data such as:

- GHG emissions of the scenario;
- GHG emissions by sectors and subsectors;
- Types of GHG emitted;
- Cumulative discounted costs per period[7], per sector, and type of costs;
- Total energy imported by energy types and per subsectors;
- Total energy mix and per subsectors;
- Total Local energy production by generation type and per subsectors.

Figure 25. Structure of TEMOA's excel dashboard template



[7] The variable cost occurring in 2015 represents the total variable cost related to energy import occurring within the time frame.

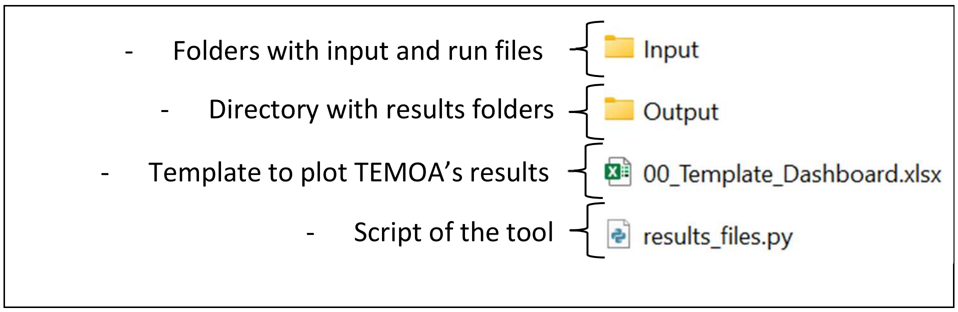
The sector-based emissions inventory of the City of Toronto includes 3 sectors, whereas 4 sectors are modeled in TEMOA (

Figure 4). However, emissions of the energy sector in TEMOA can be redistributed to the building, transportation and waste sectorsEmissions from charging stations belong to the transportation sector. Emissions of districts energy subsectors belong to Buildings. Emissions of electricity, natural gas and renewable natural gas imports are attributed to the trade energy subsector, so they can be redistributed to the 3 main sectors based on the shares of their energy consumptions.

The results files generator

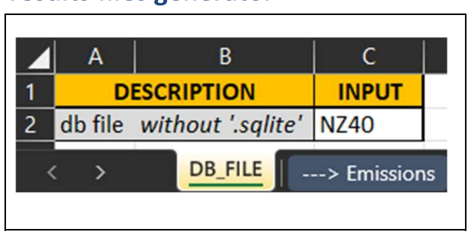
If disaggregated results are required, run the *results_files.py* tool from the *results_files* folder (Figure 26).

Figure 26. Structure of the results_files folder



This tool transforms TEMOA-TO outputs from the SQLITE output database specified in the *input.xlsx* file located in the *results_files/Input* folder. The name the SQL file to extract is to be filled in the DB_FILE sheet (Figure 27). Other sheets define the details of the SQL request.

Figure 27. Database input of the results files generator



	A	B	C
1	DESCRIPTION		INPUT
2	db file *without '.sqlite'*		NZ40

DB_FILE | ---> Emissions

To run the results files generator, open an Anaconda Prompt and enter the command from Figure 28 followed by enter. Note that the prompt after # are comments and not commands.

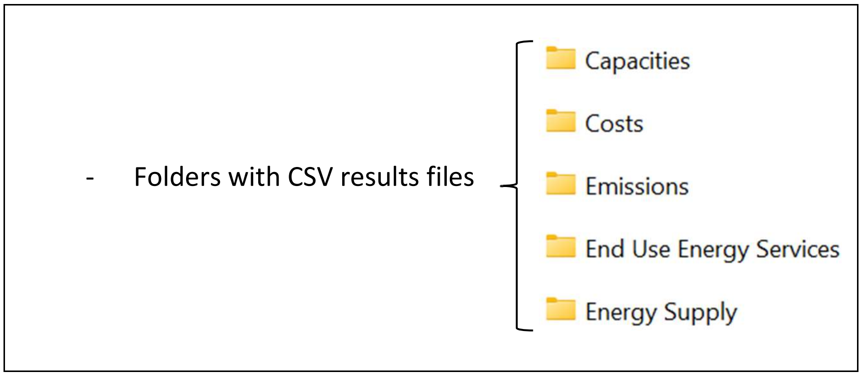
Figure 28. Extraction of TEMOA result files

Anaconda Prompt

```
activate temoa-py3
cd [path to results_files folder in TEMOA directory]
Python results_files.py #Execute the results_files tool
```

At this point, the script may extract data from the SQLITE database and create a folder named as the scenario in the *Output* folder. The scenario output folder includes five sub-folders classifying the results files (Figure 29). These folders include CSV files in a standard database format, meaning it has a column corresponding to the value of data and a few other columns corresponding to the attributes of the data. This format is the preferred format for pivot table creation as well as dashboard use such as PowerBI or Datastudio.

Figure 29. Architecture of a scenario output folder extracted by *results_files.py*



1.7 Other tutorials for TEMOA-TO

This section introduces more advanced concepts on the use of TEMOA-TO, from scenario creation to debugging. However, modelling expertise cannot be summarized in few pages.

1.7.1. Use data visualization features

Using this functionality requires basic understanding and knowledge of coding in Python language.

Open the script in Visual Studio

TEMOA provides natively data visualization features through a Python script. This functionality requires a SQLITE file as input which can be generated from a SQL file using the instruction provided in Figure 22.

To use the visualization tool, open the script at the following address:

TEMOA-TO/data_processing/Network_diagrams.ipynb

To open it, the easiest way is to use Visual Studio Code, another IDE can be used if it can deal with IPYNB files.

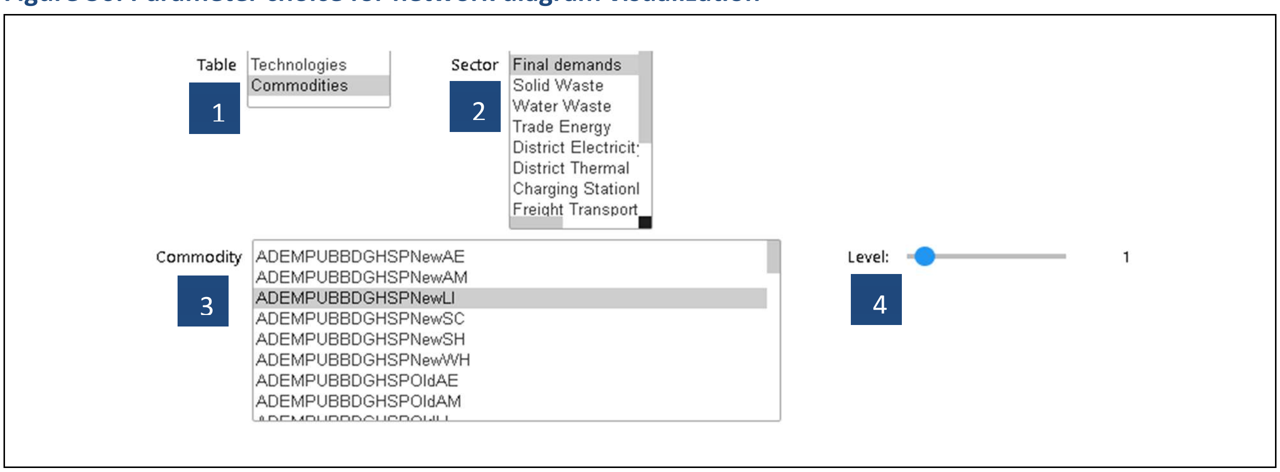
- Open Visual Studio Code;
- Use CTRL+O to open a new file;
- Select the address *TEMOA-TO/data_processing/Network_diagrams.ipynb*;
- Select temoa-py3 environment by clicking at the top left corner of the screen;
- Run the code by using CTRL+ENTER and select temoa-py3 as interpreter.

Generate network diagrams for technologies and commodities

Go to the corresponding block;

1. Select the table (technology or commodity);
2. Select the sector of demand;
3. Select the specific technology or commodity;
4. Select the level of detail with the slider, level 1 or less is sufficient most of the time.

Figure 30. Parameter choice for network diagram visualization



5. To export the graph as a PNG, uncomment the following code line:

```
#graph.render('dtree_render',view=True)
```

Technology data look-up

Go to the corresponding block and enter the label of a technology, then press enter.
The parameters printed are discretized by period and vintage of the model, the parameters included are:

- Input commodity;
- Output commodity;
- Efficiency;
- Existing Capacity;
- Lifetime;
- Investment Cost;
- Fixed Cost;
- Variable Cost.

Please note that parameters not included in this list will not be printed but are still included in the model.

Technology/commodity look-up tool

Go to the corresponding block and enter the label of a technology or a commodity, then press enter.
The script provides the name of the commodity or technology looked-up.

1.7.2. Modify a scenario

Modify demand, new technologies and constraints for scenario purposes is possible under certain rules. The most important rule is to avoid modifying values which would require a recalibration, more detail is provided in the next sections.

To minimize the debugging effort the best practice when modifying a scenario, is first to copy-paste the file to modify from the *0_Base_model* folder to the same location in the scenario folder, all the changes are then to be processed on the file in the scenario folder which will overwrite the one in the *0_Base _model* folder (see. 0)

Change the demand split

The architecture technologies in the demand folder can be tuned. However, modifying an architecture technology with no time period variation (e.g., CapacityToActivity, DemandSpecificDistribution, ExistingCapacity, Efficiency, LifetimeTech) would lead to a deep recalibration of the model. As such it is advised not to modify those parameters.

The user can tune the demand and the demand split (Demand, TechInputSplit) parameters. To avoid calibration issues, do not modify the historical year (2016-2022). For future years (2023-2050) complete freedom is allowed on tuning these parameters.

The main rule to follow for the demand split is to keep the sum of a technology input (or output) split under one.

Modify new technologies

According to new data available, it is important to update the model with the newest economic and physical assumptions. Please note that this tutorial does not apply for existing (_EX) and calibration technologies (_16) but only for technologies available after 2023 (_23;_25;_35; ...). To modify existing and calibration technologies, please refer to Calibrate or recalibrate existing years1.7.4.

To modify new technologies, refer to the *0_Base_model* folder and then the subsector of interest. The modifiable technologies are included in the *2_New_technology* folder. The best practice is not to modify directly in the *0_Base_model* folder but to copy paste the following file in your *scenario* folder. For extensive details on technologies, especially their nomenclature and units, please refer to the nomenclature in the *documentation/Nomenclature* folder.

Any of the input file in the *2_New_technology* folder can be modified the main rules to follow being:

- **CostFixed** and **CostInvest** are to be input by unit of capacity in constant k (2016) CA$;
- **CostVariable** are to be input by unit of output activity in constant k (2016) CA$;
- **EmissionActivity** is to be reported by unit of output;
- **GrowthRateMax** and **GrowthRateSeed** are calculated in the corresponding file. The rules to follow are described in Table 5.

Add additional technology

As indicated in the best practice, it is advised not to add additional technologies directly in the *2_New_technology* folder but rather in a *4_Add_technology* folder that needs to be created with the same architecture as other files: with an *Input* and *Output* folders.

To add a new technology properly, the first thing is to get the associated end-use commodity label that the technology will provide. To find a reference technology, the nomenclature should be used. The **Efficiency** table including the reference technology may be referred to. For instance, if creating a new dishwasher technology, the reference is an existing technology of dishwasher in residential buildings (e.g., RESBDGAPAOldDWA______STDELC_16). The *RESBDG_Efficiency.csv* table, includes the commodity label produced by the reference technology (in previous example, it is EUERESBDGAPAOldDWA).

To define the technology minimum input data requirement includes:

- **Technology** name as well as **commodity** name (if not already existing) should also be populated in the corresponding table;
- **Efficiency** should be populated for every period of the lifetime of each vintage. It is a crucial parameter as a technology does not exist in the database without an input efficiency;
- **CostInvest** also needs to be populated to allow the model to invest in a vintage of a technology;
- **CapacityToActivity**, **LifetimeTech** should also be populated for the technology;
- Any other relevant parameter should be input in the corresponding table.

Modify policy constraint

All the policy constraints can be found in the policy folder of a scenario. For each policy, a corresponding excel file to calculate the constraint is provided. Each file is built similarly with the corresponding colour code:

Figure 31. Colour code of policy file

In the 'Constraint_Calculation' sheet, yellow highlighted data correspond to input assumptions. By directly modifying this input assumptions, it is possible to tune the different policies.

Finally, to integrate the policy in the model, the 'Data_output' sheet should be copy-pasted in the Input folder in the corresponding CSV file.

Add a new constraint

To create a new constraint, it is possible to start from scratch or from a similar existing constraint calculation file. When the constraint is created, the address should be referenced in the *Import_adress.txt* file.

The updated scenario can now run. Keep in mind that the overall set of constraints should be compatible to provide a solution It could be useful to add constraints progressively to spot infeasibilities as described in 1.8.3.

Modify energy supply assumptions

The energy supply assumptions significantly impact the final system; therefore, they are major assumptions for the model. These assumptions are easily accessible in the folder: *data_files/import_data/0_Base_Model/4_Energy/1_Trade_energy*

The energy cost assumptions are included in the *TRAENE_CostVariable.csv* file, the cost of importing a Terajoule of energy is reported in k (2016) CA$/TJ. It is possible to tune energy cost per period and per subsector. The energy supply limitations as well as the electricity import rule are included in the TRAENE_MaxActivity.csv file. The energy ban rules are designed in the Energy_Ban.xlsx file and summarized in Table 16.

o	Allowed in future years no supply limit
-	Allowed in future years but limited supply
x	Banned in future years

Table 16. Energy ban rules

Energy	PUBBDG	RESBDG	INDBDG	COMBDG	FRETRA	LDITRA	PASTRA	PUBTRA
Electricity	O	O	O	O	O	O	O	O
Natural gas	O	O	O	O	-	-	-	-
Synthetic gas	-	-	-	-	-	-	-	-
Biomethane	O	O	O	O	-	-	-	-
Propane	O	O	O	O	-	-	-	-
Geothermal energy	O	O	O	O	X	X	X	X
Biomass	-	-	O	-	X	X	X	X
Heavy Fuel Oil	-	-	-	-	-	X	X	X
Light Fuel Oil	-	-	-	-	-	X	X	X
Hydrogen	O	O	O	O	O	O	O	O
Kerosene	-	-	-	-	-	X	X	X
Wood Pellet	-	-	O	-	X	X	X	X
Aviation Gasoline	X	X	X	X	O	O	X	X
Aviation Turbo Fuel	X	X	X	X	O	O	X	X
Diesel	X	X	X	X	O	X	O	O
Gasoline	X	X	X	X	O	X	O	O
Cellulosic Ethanol	X	X	X	X	-	X	O	O
Ethanol	X	X	X	X	O	X	O	O
Renewable Diesel	X	X	X	X	-	-	-	O
Bio Diesel	X	X	X	X	O	O	O	O
FT Diesel	X	X	X	X	-	X	-	-
Bio Jet	X	X	X	X	O	O	X	X
Synthetic Jet	X	X	X	X	O	O	X	X
Coal	X	X	-	X	X	X	X	X
Coke	X	X	-	X	X	X	X	X
Pet Coke	X	X	-	X	X	X	X	X

In the Energy_Ban.xlsx, the boxes in Table 16 that have O are set to 1 in the file, the boxes that have x are set to zero in the file, and all the boxes that have - are 0.5

1.7.3. Create your own scenario

To create your own scenario the steps to follow are the following:

1. Create a new folder in *data_files/import_data* (e.g., 8_My_scenario);
2. Add the scenario address in *data_files /Import_adress.txt*;
3. Open *Generate_SQl.py* with an IDE or Notepad;

Figure 32. Scenario definition in *Generate_SQL.py* script

```
#this function filters the data and creates txt files that will be used to generate the SQL data
def Generate_SQL(Folder, adress, Label, Adress_data, Adress_energy, Adress_policy):

    Input_path = Folder + adress + 'Input/'
    Output_path=Folder + adress + 'Output/'

    Scenario = ['import_data','',
    '0_Base_Model',
    '1_Business_As_Usual',
    '2_Business_As_Planned',
    '3_Net-zero_2050',
    '4_Net-zero_2040',
    '5_Net-zero_2050_PureOpt',
    '6_Net-zero_2040_PureOpt',
    '7_Target-based_PureOpt',
    '8_My_Scenario'
    ]
```

4. Add 8_My_scenario in the list of scenarios.

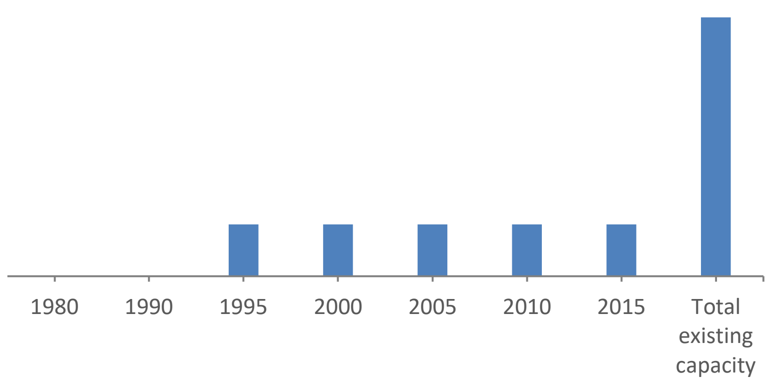
The scenario folder can now be imported through the *Generate_SQL.py* script. The folder can now be filled with constraints and technology data.

1.7.4. Calibrate or recalibrate existing years

Technology type

The pre-existing technologies (meaning existing before year 2016) are the one including the "_EX" suffix, the existing capacities related to those are uniformly distributed among the lifetime of the technology with a 5-year gap as shown in Figure 33 (e.g., RESBDGAPAOldRAG______STDNGA_EX).

Figure 33. Illustration of distribution of existing capacity in different vintages



The calibration technologies used to calibrate existing years between 2016 and present time are the technologies which ends by "_16" (e.g., RESBDGAPAOldSHFUR___STDBMA_16).

All new technologies, useful for future year optimization ends with the initial availability year starting from 2023 "_23", "_25", "_35", etc. (e.g., RESBDGAPAOldLIFLUT12STDELC_23).

Calibration of the base year

The model is to be calibrated on a baseline. The previous modelling, CityInsight, is calibrated on energy reporting of 2016 GHG inventory. Year 2016 to current year is calibrated on CityInsight energy consumption projection. A finer calibration on historical data could be achieved but is only relevant for specific sectors (e.g., impact of the covid crisis on the transportation demand).

The goal of calibration is not to match the values from CityInsight, but rather to tune assumptions to reach the tolerance of 5% in energy consumption.

Calibration of historical years

Calibrate "_16" technologies is about constraining the model to invest in technologies according to assumed or historical technology share from 2016 to present year.

The model will be provided with calibration for years 2016 to 2022. However, any slight change in input data and assumptions can lead to a compilation or optimization error. In case of modification, the following methodology can help the user to recalibrate (note that for years 2016 to 2022 calibration data is partial). Furthermore, as yearly data becomes available it is important to update the model to calibrate according to new data. Accordingly, this process is expected to be easily reproductible and automatized.

The whole idea of calibrating the model is to force the model to reproduce reported energy consumption from 2016 to present year. To do so, two constraints are applied to year 2016 - 2022:

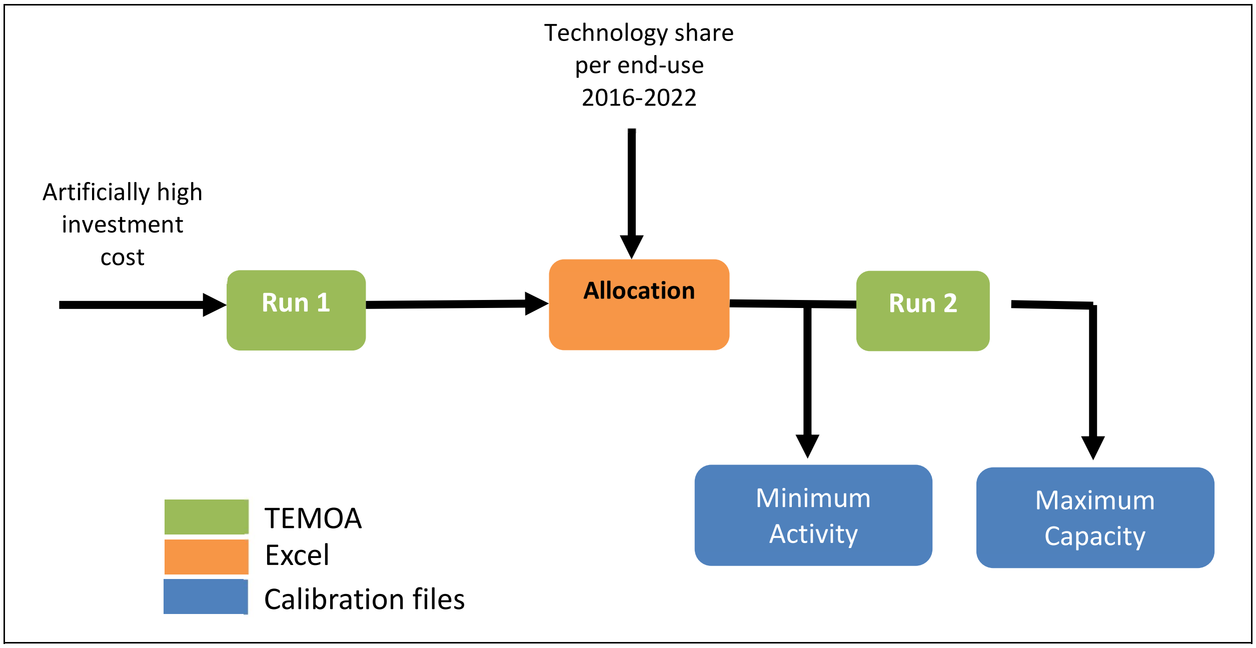
- Minimum activity constraint, forcing a specific technology to produce a given output.
- Maximum capacity constraint, forcing the model not to invest more than required.

To get the value of those two constraints for each technology, the goal is to get the minimal value of capacity to be invested in to provide the required amount of end use. To force the model to do so, a very high investment cost of calibration technologies is used (10^10 k$/cap) for all periods. Then, minimum required activity and capacity per end use is allocated to the technologies according to assumed or historical technology split.

After calibrating the model, we force to not invest anymore in "_16" technologies after 2023. To do so, the investment cost of those technologies follow the trend:

- 0 k$/cap for 2016 – 2022;
- 10^10$/cap for 2023- 2050.

Figure 34. Process chart, calibration of historical years



In detail, the following procedure explains how to calibrate the model. It can be applied for the entire model at once. However, to minimize the chance of getting errors ESMIA's advice is to prefer to calibrate by subsector.

Table 17. Calibration methodology

Step	Instruction
1	Apply a high investment cost for calibration technologies (10^10 k$/Cap) for all periods in all CostInvest CSV file.
2	Remove MinActivity and MaxCapacity constraints from new technology folder.
3	Run the model[8]. Open the XLS file generated as output from the model (found in the sub folder with the name of the scenario in the “data_files” folder).
4	Open *import_data/0_Base_model/sector/2_New_technology/Calibration.* Open the excel file for “_16” calibration: - Copy data from Activity_’Sector’ in file generated in step 2; - Paste it in the calibration excel file in the corresponding sheet; Change the Technology Split if necessary.
5	The MinActivity parameter is automatically generated. Extract it as CSV and place it in *import_data/sector/2_New_technology/Input.*
6	Run the model[8]. Open the XLS file generated as output from the model.
7	Open *import_data/0_Base_model/sector/2_New_technology/Calibration.* Open the excel file for “_16” calibration: - Copy data from Capacity_’Sector’ in file generated in step 5; Paste it in the calibration excel file in the corresponding sheet.
8	The MaxCapacity parameter is automatically generated. Extract it as CSV and place it in *import_data/sector/2_New_technology/Input*
9	Apply 0 investment cost for all “_16” technologies in the period 2016-2023.[9]
10	The model is now calibrated.

1.7.5. Create SQL queries

To create a SQL request, basic SQL knowledge is required, and a deeper understanding of the architecture of both the *input.xlsx* file (in the *results_files/Input sub-folder)* and TEMOA-TO SQLITE outputs.

The best practice for SQL query creation is to start from one of the existing queries by copy-pasting it into a new sheet in the *input.xlsx* file. Additionally, to help with SQL query design and visualization, it is highly advised to open both the SQLITE output database (with *DB Browser for SQLite* software) and the nomenclature.

[8] Period definition can be changed to cut solving time.
Minimum requirement is 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2050, 2051.
[9] Exception for some technologies in the building sector.

In the *input.xlsx* file, the sheets following 'DB_FILE' define SQL requests to create the corresponding CSV files. The name of those sheets begins by a letter which defines the output folder in which the CSV file is saved as per Figure 29:

- E- for Emissions folder;
- N- for Energy Supply folder;
- C- for Capacities folder;
- D- for Costs folder;
- A- for End Use Energy Services folder.

The Figure 37 is an example of the template of those input sheets. The step to fill this sheet as are includes:

1. First, the first line of the CSV files should be filled with a general description of the request which helps to understand the granularity of data aggregation.
2. Secondly, the type of outputs aggregated should be selected from the list of the seven tables suggested. More details on the attributes of those tables are presented in Figure 35. Then, select the column to aggregate the data from the different attributes.

Figure 35. Architecture of the outputs tables of a TEMOA database

(a) Technologies capacity per periods

Name	Type
Output_CapacityByPeriodAndTech	
regions	text
scenario	text
sector	text
t_periods	integer
tech	text
capacity	real

(b) Technologies capacity per vintage

Name	Type
Output_V_Capacity	
regions	text
scenario	text
sector	text
tech	text
vintage	integer
capacity	real

(c) Technologies cost per vintage

Name	Type
Output_Costs	
regions	text
scenario	text
sector	text
output_name	text
tech	text
vintage	integer
output_cost	real

(d) Technologies emission per time slice

Name	Type
Output_Emissions	
regions	text
scenario	text
sector	text
t_periods	integer
emissions_comm	text
tech	text
vintage	integer
emissions	real

(e) Technologies incoming flow per time slice

Name	Type
Output_VFlow_In	
regions	text
scenario	text
sector	text
t_periods	integer
t_season	text
t_day	text
input_comm	text
tech	text
vintage	integer
output_comm	text
vflow_in	real

(f) Technologies outgoing flow per time slice

Name	Type
Output_VFlow_Out	
regions	text
scenario	text
sector	text
t_periods	integer
t_season	text
t_day	text
input_comm	text
tech	text
vintage	integer
output_comm	text
vflow_out	real

(g) Dual values of model constraints

Name	Type
Output_Duals	
constraint_name	text
scenario	text
dual	real

Attribute	Description	Attribute	Description
regions	name of the region	output_cost	cost value
scenario	name of the scenario	emissions_comm	GHG type
sector	subsector of the technology	emissions	emissions value
vintage	vintage of the technology	input_comm	input commodity type
t_periods	year modelled	output_comm	output commodity type
t_season	season modelled	vflow_in	input flow value
t_day	daily time slice modelled	vflow_out	output flow value
tech	technology's ID	constraint_name	constraint type
capacity	capacity value	dual	dual value
output_name	type of cost		

3. Third, to have more details on technologies, more aggregation can be applied through the nomenclature of the technologies. Nomenclatures are defined by sectors, the architecture can be found in the *documentation/Nomenclature* folders in TEMOA directory. The nomenclature will be combined with the Dictionary which includes the meaning of each label (Figure 36).

Figure 36. Input files for results files generator's directory architecture

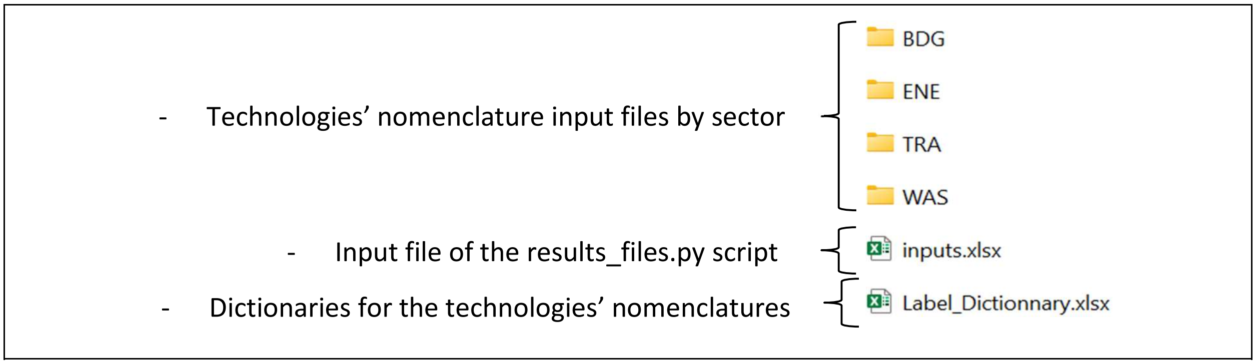
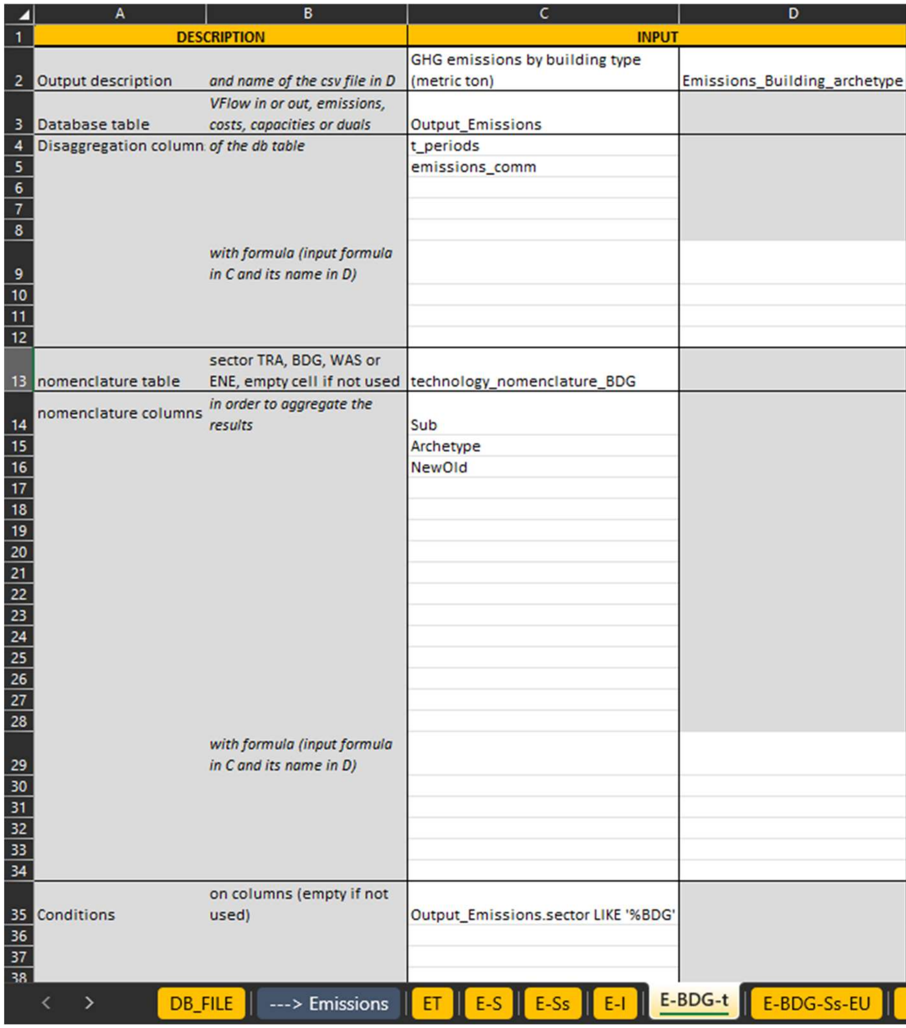


Figure 37. Template of the input file for the results files' generator



	A	B	C	D
1	DESCRIPTION		INPUT	
2	Output description	*and name of the csv file in D*	GHG emissions by building type (metric ton)	Emissions_Building_archetype
3	Database table	*VFlow in or out, emissions, costs, capacities or duals*	Output_Emissions	
4	Disaggregation column	*of the db table*	t_periods	
5			emissions_comm	
6				
7				
8				
9		*with formula (input formula in C and its name in D)*		
10				
11				
12				
13	nomenclature table	sector TRA, BDG, WAS or ENE, empty cell if not used	technology_nomenclature_BDG	
14	nomenclature columns	*in order to aggregate the results*	Sub	
15			Archetype	
16			NewOld	
17				
18				
19				
20				
21				
22				
23				
24				
25				
26				
27				
28				
29		*with formula (input formula in C and its name in D)*		
30				
31				
32				
33				
34				
35	Conditions	on columns (empty if not used)	Output_Emissions.sector LIKE '%BDG'	
36				
37				
38				

Name of the output file (in D2) and its description (in C2).

Name of the database's table to aggregate.

Database (db) column name to aggregate (it could be a formula inputted, for the first one, in C9 and its name in D9).

If required, input the name of the nomenclature table used for the aggregation.

If required, input nomenclature column name to aggregate (it could be a formula inputted, for the first one, in C29 and its name in D29).

If required, input conditions to filter attributes, it can be attributes from the nomenclature as well as the database table.

Warnings! Names of formulas must be different from the database columns names and must not contain space. In formulas, columns name must be preceded by name of its table and a dot (see example above, cell C35). Columns and table names must be the same since SQL queries are sensitive to capital letters. For a more user-friendly use, drop down lists are implemented in db table, aggregation columns, nomenclature table, and nomenclature column.

1.8TEMOA model debugging and main issues

1.8.1. Avoid changing the core model assumptions impacting historical years

Changing the core model assumptions may lead to infeasibility issues to and require recalibrating the model which may be a long process (see: 1.7.4). To avoid calibration issues, one should avoid changing parameters that are impacting the historical years. More specifically the parameters in the sub-folder "demand" found in the different sector and subsector folders are the most sensitive. In the demand folders, all parameters which do not have a period column are very sensible and any change will lead to calibration issue. Efficiency, DemandSpecficDistribution, and CapacityToActivity are the most sensible tables. Conversely, it is possible to modify the Demand table as long as the change in the demand is not too brutal between historical years and future year which may be incompatible with the inertia constraint.

1.8.2. Follow the Importation guidelines

The importation phase which coverts the data from CSV files to a format read by TEMAO-TO may lead to debugging issues linked to a problem in input values or to data reference. This error could happen at any preprocessing step from the generation of the SQL file to its transformation to SQLITE, or compilation of the TEMOA instance (i.e., Creation of a LP optimization file including all equations of the problem from the SQLITE input data).

Best practices to minimize importation issues

1. **Make sure the CSV files are clean**, the CSV files are not calculation files but input files, if a calculation is required to generate CSV file make sure to do it in an external EXCEL file and not in the CSV. CSV should not contain more columns than expected or it may create compilation issues.
2. **Do not apply multiple times a same parameter to the same variable**, this may lead to a warning informing that a duplicate of value attribution is found in the SQLITE file.
3. **Do not use multiple time a same CSV parameter type in a folder**, one may overwrite the other. In this case, files should be combined, or a new folder should be created.
4. **Use the following formalism for CSV name**, *'Prefix'_'Parameter name'* (e.g., PASTRA_Efficiency or BAP-BDG-1_groups), do not use '_' in the prefix as it is a parsing symbol (i.e., use BAP-BDG and not BAP_BDG).
5. **Use the following guidelines to create group-based constraints**:
    a. Do not fill the groups column in the tech_groups parameter fields;
    b. Add the subsector ID in a group name (e.g., PASTRA-EV_groups).
6. **Make sure to not have spaces in the address of the TEMOA-TO** depository (e.g., *C://Users/John Smith/TEMOA-TO*, will not be compiled correctly. Use instead *C://Users/John_Smith/TEMOA-TO*).

Debugging methodology

In case importation issues are occurring even with the best practices, the following points describe the most frequent issues and the methodology to address them.

If issue happens at the SQL generation phase, it is certainly an issue related to the way CSV files are built, make sure to follow the previous best practices number **4. and 5.**

If issue happens at the conversion of SQL to SQLITE, the issue is related to duplicates in SQL file or value error, make sure to follow the previous best practices number **1., 2. and 3.**

If issue arises at the compilation and creation of the TEMOA instance step, a wider range of issues may be the cause, first make sure to follow the guidelines number **1., 2. and 3.** Most of the time an issue at this stage without previous warning or error is a reference issue. The problem could be a requirement issue (i.e., trying to attribute values to a parameter while requirements for value attribution are not fulfilled).

This type of debugging issue is very frequent and is directly linked to the way TEMOA creates the instance, think about it as a LEGO construction:

i. First, it creates **the basic bricks** for the building by importing the technologies, commodities, and group databases;
ii. Then, it creates **the network of technology** by importing the efficiency database including how technologies are linked to commodities and the transformation factor applied between input and output;
iii. Then, it **characterizes the network** using the different attributes: Lifespan, Costs, CapacityFactor, etc.;
iv. Finally, it **constrains the network** by applying all sorts of constraints: GrowthRate, TechSplit, MinActivity, etc.

What is important to understand is the priority order on defining a model input data, and the reference required to add additional element. It is impossible to define the efficiency of a commodity between two technologies if the technology and commodity are not defined in the required tables. Similarly, it is impossible to apply a cost to a technology which is not part of the technology network (i.e., which has no efficiency filled). This type of misconstruction would lead to reference issues and impossibility to create a component. It may be corrected by populating the reference CSV files.

If issue arises at the CPLEX launch phase, make sure to follow previous best practices number **6.**

1.8.3. Typical debugging methodology

This Main objective of this section is to introduce a methodology to help users which may face debugging issues using and developing in TEMOA-TO. Note that this section is not exhaustive as the debugging field is large. For additional support on debugging, please refer to the following resources:

- ✓ TEMOA community: https://groups.google.com/g/temoa-project
- ✓ TEMOA documentation: https://temoacloud.com/temoaproject/Documentation.html

While the original model version of the model can be solved without difficulties, users may certainly want to build their own scenarios and policies, which may lead to debugging issues.

Best practices to minimize debugging issues

1. **Track change and test it**; an important advice to keep in mind when developing new functionalities constraints in the model, is to track the changes and run the model on a regular basis to see the impact of changes. Making too many changes at once may certainly lead to an issue, whether compilation or solving.
2. **Keep the last running version as master**; in the development phase, a good practice is to keep two versions of the model. The master version, which is running perfectly, and the development version which is the one used to test changes. When the development version is mature enough the changes may be integrated to the master version.
3. **Save regularly intermediate version,** it may seem to be a trivial advice, but it is a no regret action to track intermediate version.

Debugging methodology

Even if the best practices are applied, debugging issues may occur, a first batch of issue happens at the compilation steps of the algorithm:

- ✓ PREPROCESSING: SQL generation;
- ✓ PREPROCESSING: SQLITE conversion;
- ✓ TEMOA: Reading data files;
- ✓ TEMOA: Creating Temoa model Instance.

If facing issues at the PREPROCESSING steps, please refers to 1.8.1. Solving the model itself is the step which may lead to the highest probability of debugging issues, depending on the solver different issues may be faced. Using CPLEX two main infeasibility issues can occur:

1. **Presolve infeasibility**, (all solvers do not presolve the problem), infeasibility at this step means that constraints are giving contradictory orders to a same variable of the model (e.g., PV Capacity <10 GW and PV Capacity >12 GW).
2. **Solve infeasibility**, if the algorithm does not converge toward the optimal value. At this stage infeasibility may be related to incompatible constraints applied on different variables but those variables are linked (e.g., GHG emission <1 Mt CO_2e and Natural gas consumption >20 PJ, may create infeasibilities as both GHG emission and consumption of energy which produces GHG emission are constrained).

Those examples may seem to be trivial examples but as the number of technology and constraint increase in an energy s and waste system model, finding and correcting the right constraints may become harder. At this point the main debugging challenge is to find the infeasible set of constraint. The next bullet points summarize the debugging methodology, note that this methodology is independent to the solver used.

i. **Decompose the problem into smaller parts**, first decompose the size of the problem to find the subsector subject to infeasibility. To do so import one module after another by commenting addresses in *import_adress.txt*. Please make sure to always import the energy modules. To speed up this phase it is possible to decrease the time period resolution.
ii. **Locate the constraints,** after identifying the subsector which lead to infeasibility issues, the objective is to find the specific incompatible constraints. For existing scenarios, the list of constraints is provided in Annex A. Some constraints are more likely to create infeasibilities, Table 18 summarizes all constraint types in scenarios and their risk of creating infeasibility. To locate infeasible constraints 2 strategies can be used:
    a. **Activate constraints progressively,** first deactivate all constraints, the model is supposed to converge, then progressively add back constraints from the least sensitive to highest risk, run the model at each iteration. The tipping point can be found, where adding one additional constraint may create infeasibility, this is the constraint to correct.
    b. **Deactivate constraints progressively,** conversely, deactivate progressively the constraints from the higher risk one to the least sensitive until finding the tipping point where the model is running. If the best practices are followed, and changes are tracked this methodology may be faster.
iii. **Fix the constraint**, after locating the infeasible constraint the constraint can be tuned, there is no particular methodology it will depend on the use case.
iv. **Reactivate the constraints,** when the constraint is corrected and the model converge, deactivated constraints may be progressively added back. As multiple infeasibilities may appear, it is highly recommended to continue to add constraints progressively and to keep track of the constraint activate and deactivate.

Table 18. Constraint type and sensitivity to infeasibility

#	Constraint type	Location	Example	Risk of infeasibility	Comment
1	Technical constraints	/Base Model /Sector /Subsector	TechInputSplit TechOutputSplit	+	
2	Calibration constraints	/Base Model /Sector /Subsector /2_New_Technology	Max Capacity Min Activity	+	Not leading to issues when nothing is changed on historical years.
3	Growth Constraints	/Scenario /Sector /Subsector /2_New_Technology	Growth Rate Seed GrowthRateMax	++	
4	Policy constraints	/Scenario /5_Policy/ /x_Sector	MaxGenGroupTarget MinShareGroup ….	+++	
5	Inertia constraints	/Scenario /5_Policy /4_Energy	MinGenGroupTarget MinShareGroupTarget	+++	
6	Global constraints	/Scenario /5_Policy /5_EmissionLimit	EmissionLimit	+++	

2. The Linking Tool

This section describes the Linking Tool structure and operation in order to pass from the long-term planning model (i.e., TEMOA-TO), to the short-term planning model (i.e., SILVER-TO). It describes what the Linking Tool is, how it works, how to use it, and finally what the results look like and how it is linked with SILVER-TO.

2.1 The structure of the Linking Tool

The Linking Tool is a Python script used to link the long-term and short-term planning models. It aims to maximize models' complementarity and to reinforce the value for decision makers. In other words, it enables communication from TEMOA outputs to SILVER inputs, and to a lesser extent from SILVER outputs to TEMOA inputs.

Part of the data used for the SILVER-TO model comes from the TEMOA-TO model. Those data are the power demand in the city, the PV and wind installed capacities, and the storage capacity for residential storage and electric vehicles. TEMOA's outputs are at the city level and must be disaggregated by areas and by time slices for SILVER inputs. Figure 38 provides a simplified scheme for the Linking Tool inputs and outputs, while Figure 39 provides a detailed framework of the Linking Tool methodology. TEMOA's outputs are first disaggregated from the city level to transformer service areas by using the population rate in traffic zones as explained in section 2.1.1. Then, they are disaggregated by time slice with various methods described below in sections 2.1.2 and 2.1.3, using power generation potential for instance.

Figure 38. Schematic illustration of the Linking Tool inputs and outputs

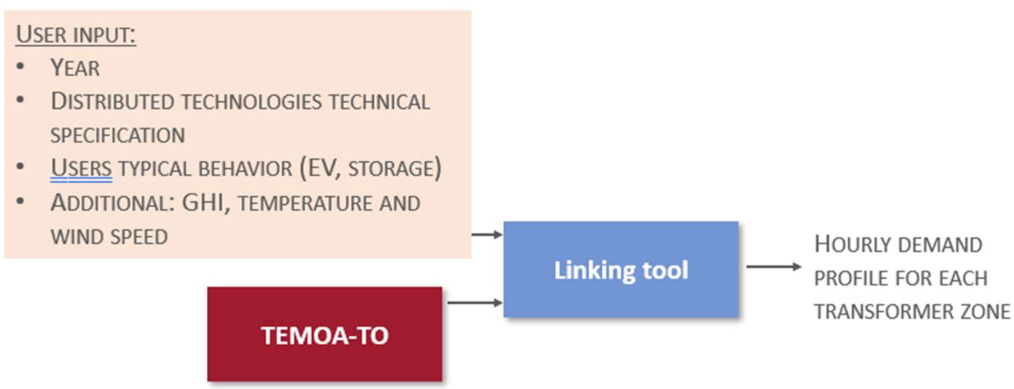
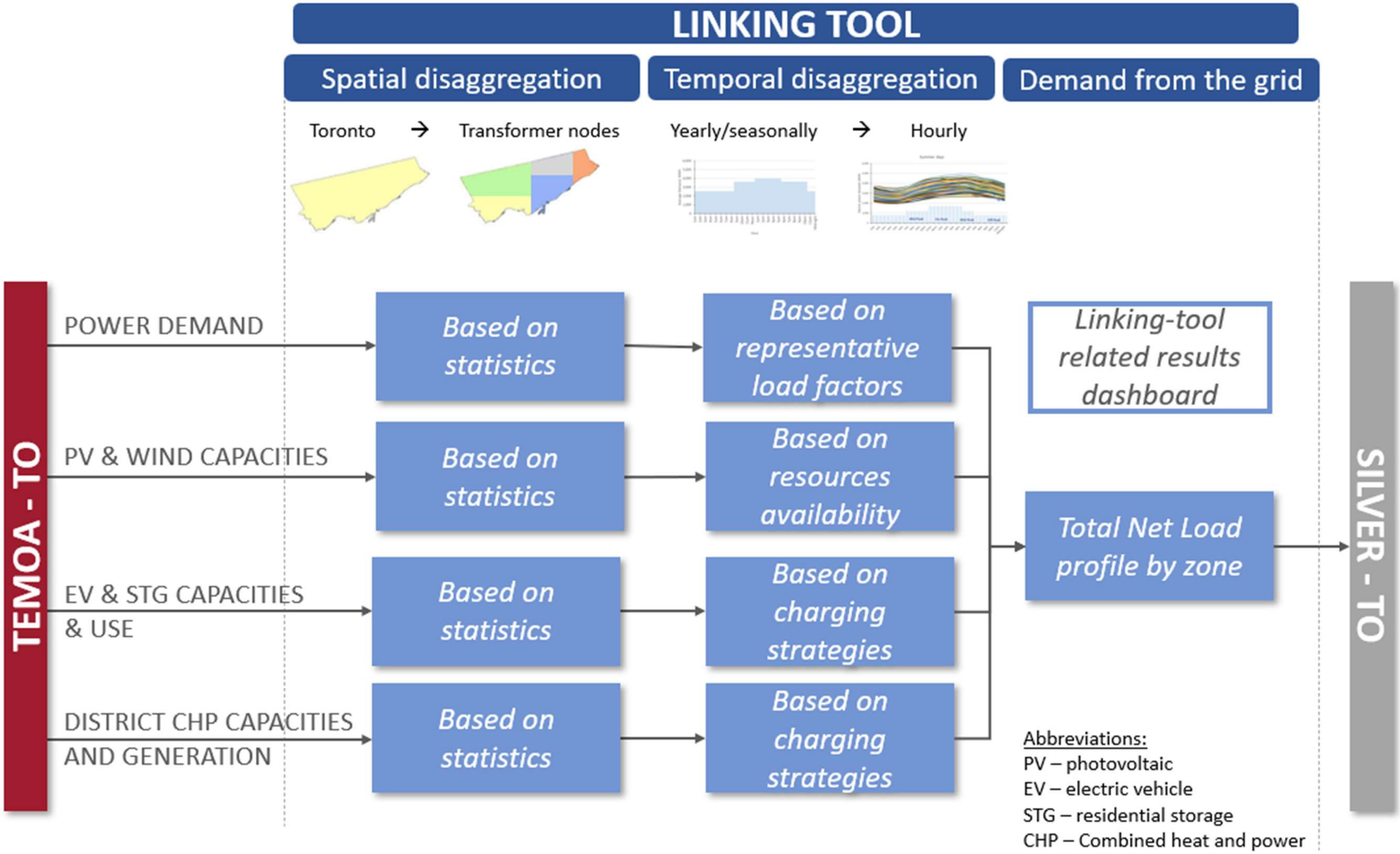


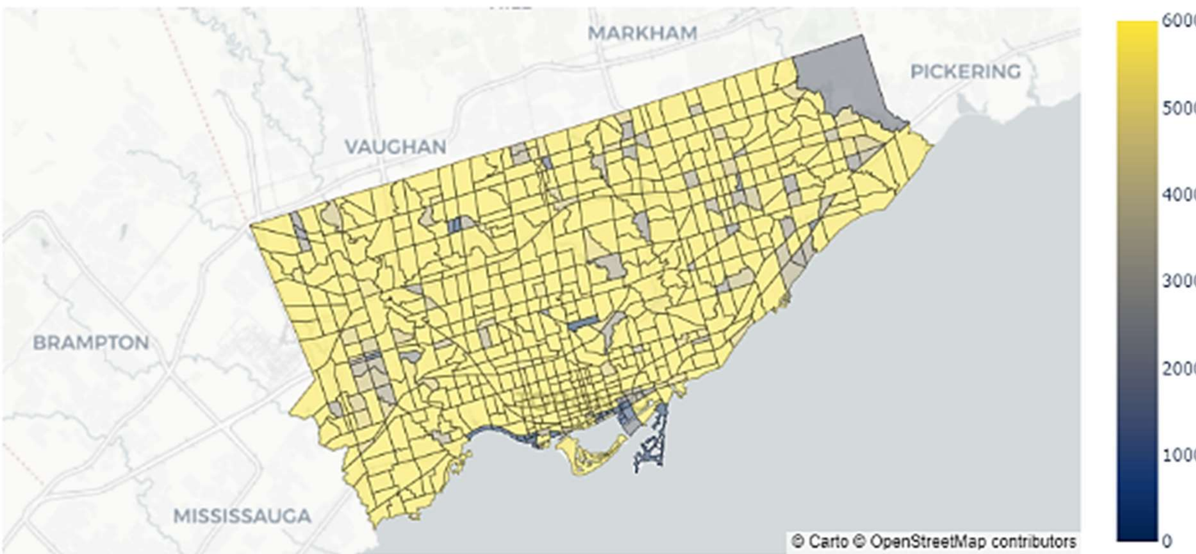
Figure 39. The Linking Tool framework



2.1.1. Spatial disaggregation

The project was initially designed to be completely comparable with Toronto's previous modelling initiative CityInsight. To assure this requirement, it was initially decided to develop a TEMOA model based on the 649 traffic zones from the City Planning department (see Figure 40). This spatial granularity is the highest level of detail available and is based on the zones defined in the Transportation Tomorrow Survey (TTS). As the input data were reviewed, precision of the modelling was decided, and knowledge of TEMOA's specific characteristics and limitations was gained; more information about solving time was available. Optimization model solving time is exponentially dependent with its number of variables; this means that the time to solve for 650 spatial dimensions would be four orders of magnitude higher than solving for one spatial dimension. As a results of this analysis, the spatial granularity of TEMOA was chosen to have an acceptable solving time so it was decided to aggregate Toronto into one zone, optimize the energy and waste system and then allocate the optimal flows and capacities to multiple zones.

Figure 40. Initial 649 parcels required granularity[10]



In the SILVER model, input data are aggregated by transformer nodes that correspond to a particular transformer service area. Those transformer nodes are represented in the SILVER-TO section 3.1.

As represented in Figure 39, for the electricity power demand, the Linking Tool first disaggregates those output data by traffic zones by multiplying it by the population rate in traffic zones (data from the City of Toronto population projections). Because the transformer nodes makeup multiple traffic zones, the values of the different traffic zones that make up one transformer zone are added up to get the values for a transformer zone. For other TEMOA's output data, the spatial disaggregation is done based on the local electricity power demand.

[10] City of Toronto (2022). TransformTO Net Zero Strategy: Climate, Energy and Resilience. Online (Accessed in February 2023): https://www.toronto.ca/services-payments/water-environment/environmentally-friendly-city-initiatives/transformto/

2.1.2. Representative power demand curves the city level

The long-term planning model, TEMOA, considers a long-term planning horizon and uses time slices to capture changing daily and seasonal operation conditions. It considers four seasons and four time slices during the day to represent demand and supply occurring during night, morning peak, day (period in the middle of the day) and evening peak. In the optimization results, TEMOA reports the total electric power demand by daily time slice and by season. However, as the input, SILVER-TO takes hourly load profiles. The Linking Tool fills this gap by transforming the average consumption per daily time slice per season into a representative hourly load curve. In other words, the Linking Tool can project hourly load profiles in any given year selected by the user using the outputs from TEMOA.

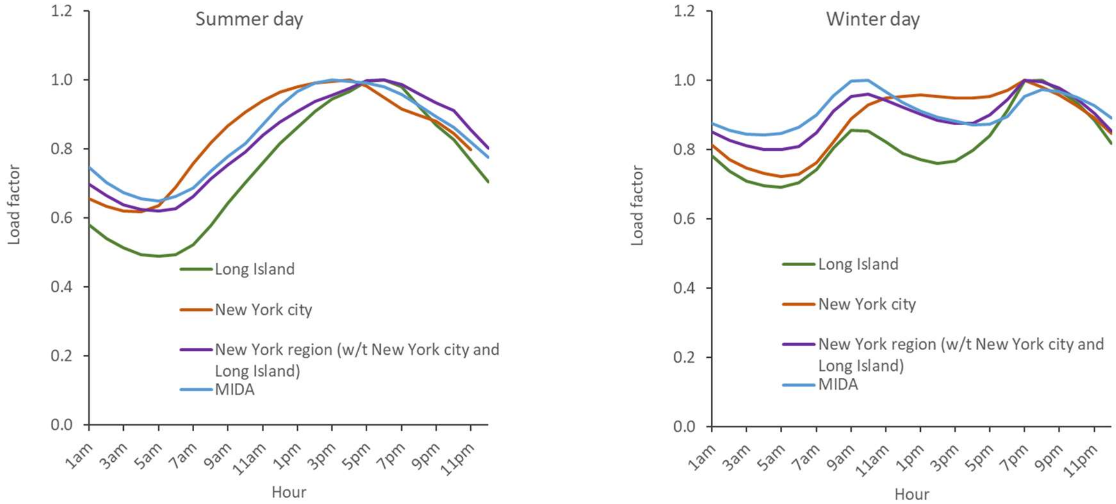
The shape of load profile in a transmission zone depends on the type of consumers and their consumption habits. The shape of load profile in a city where the majority of power consumers are households and small businesses will be different from the load profile shape of a large jurisdiction (e.g., a province or a country). Typically, provincial and country load profiles will be impacted by the large-scale consumers (e.g., industries) whose power demand will be more constant throughout the entire day. As a consequence, the shape of the total provincial or country profile will be "flatter" than the shape of the load profile in the city. Another factor that may influence consumption profile may be the type of consumption appliances that may differ by type of residences (e.g., apartment vs detached house). Data regarding Canadian load profiles in different jurisdictions and regions is scarce. Therefore, we rely on analysis based on the US electricity system context described below.

Figure 41 illustrates this effect by providing load profiles for the same day in zones of different sizes[11] (Figure 42):

- Long Island, with the majority of residential and commercial (<145 kW) consumers;
- New York City, a dense urban area with most electric consumption coming from residential (55 per cent) and commercial (45 per cent) sectors and a small share of industrial consumption (0.2 per cent);
- New York region without New York City and Long Island, where large-scale industrial electric power consumption reaches 1 per cent and commercial consumption decreases to 21 per cent;
- PJM coordinates power in mid-Atlantic (MIDA) region, where large-scale industrial consumption reaches around 27 per cent.

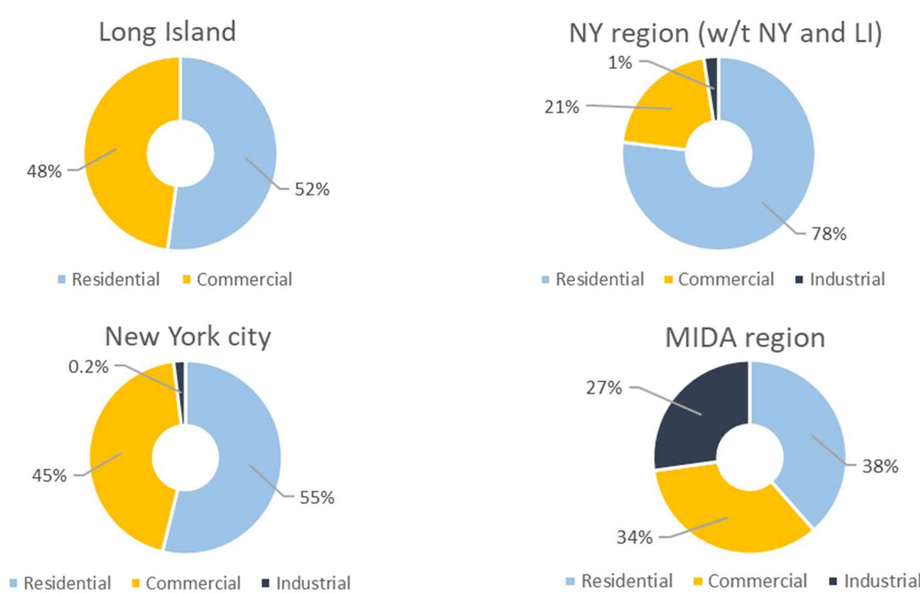
[11] PSEG Long Island (2023). Rate Information: Rates and tariffs. Online (Accessed in February 2023): https://www.psegliny.com/aboutpseglongisland/ratesandtariffs/rateinformation
EIA – Energy Information Administration (2022). Electricity Data. Online (Accessed in February 2023): https://www.eia.gov/electricity/data.php
EIA – Energy Information Administration (2023). Retail sales of electricity. Online (Accessed in February 2023): https://rb.gy/y12qor

Figure 41. Load profiles at different transmission zones



The load profiles covering smaller transmission areas, such as Long Island, may have bigger night/day load variation. The evening peak is more pronounced than in larger jurisdictions and may occur later in the evening. This is noticeable for both summer and winter days when the electric consumption in the area increases fast with people coming back home from outside of this transmission area (e.g., people living in Long Island and working in New York). Large cities, such as New York, include a significant portion of businesses employing people living in the city and consuming electricity during the day. Thus, their mid-peak may be higher and morning and evening peaks less pronounced. In larger areas but with smaller cities and communities, such as New York region without New York and Long Island, consumption profile becomes more dependent on power consumption in detached houses, appears large-scale industrial consumers, day/night load variation decreases. In large regions, such as MIDA, day/night load variation decreases even further.

Figure 42. Shares of annual electric power consumption per sector

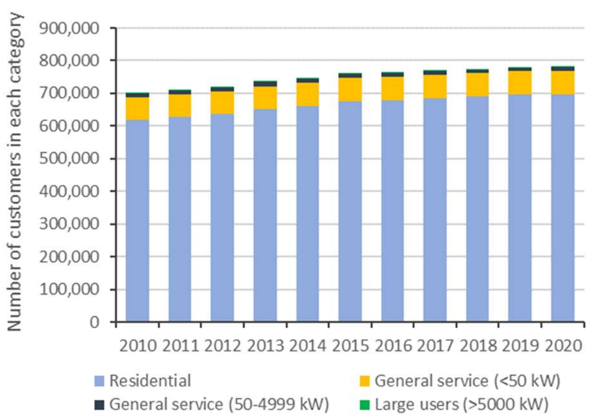


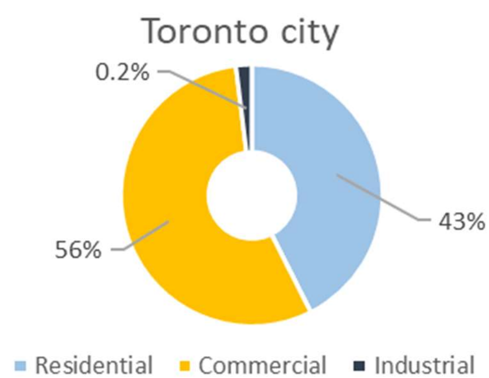
In 2020, Toronto Hydro distribution company supplied 696,627 residential consumers, 82,505 commercial consumers and 44 large-scale users (Figure 43). According to Toronto Hydro consumers under the residential category consume only 23 per cent of the electricity power in Toronto. However, at the same time, 20-30 per cent of large residential complexes/condos in Toronto were connected under General service tariffs (i.e., condo electricity consumption is covered by one electricity bill to which each resident contributes). This increases the electric power consumption related to housing up to 43 per cent. As we see in Figure 42, this makes the share of consumers per type of their end use very similar to New York City.

The specific peak periods in Toronto are defined based on the end use depending on the season[12]:

- Summer days are characterized by a dominant consumption peak that occurs between 11 a.m. and 5 p.m. due to the use of air conditioning. During the last ten years summer peak was on average 18 per cent higher than the winter peak, it reached 4,493 MW in 2020.
- Winter days typically have two more pronounced peaks: less pronounced morning peak occurs between 7 a.m. and 11 a.m. and more important evening peak occurs between 5 p.m. and 7 p.m. In 2020, Toronto Hydro reported 3,511 MW of winter peak.
- Fall and spring days load profiles represent a transition between two more extreme seasons. Based on summer and winter billing periods with time-of-use (TOU) rate, winter billing period switches to summer.

Figure 43. Electric power consumers by category in Toronto[13]





In the absence of the detailed information about load profiles of the entire city of Toronto, as well as its individual transformer (distribution) areas, load profiles for the city and its different zones were calibrated based on New York City load hourly factors for the entire year derived from historical data[14] and the

[12] OEB – Ontario Energy Board (2023). Natural gas and electricity utility yearbooks: Ontario's energy sector. Online (Accessed in February 2023): https://www.oeb.ca/ontarios-energy-sector/performance-assessment/natural-gas-and-electricity-utility-yearbooks

[13] OEB – Ontario Energy Board (2023). Natural gas and electricity utility yearbooks: Ontario's energy sector. Online (Accessed in February 2023): https://www.oeb.ca/ontarios-energy-sector/performance-assessment/natural-gas-and-electricity-utility-yearbooks

[14] EIA – Energy Information Administration (2022). Electricity Data. Online (Accessed in February 2023): https://www.eia.gov/electricity/data.php

information about seasonal consumption coming from TEMOA (Figure 44). New York City was chosen as the share of consumers per type of their end use very similar to Toronto's.

Figure 44. Schematic illustration of approach to calculate typical hourly electricity demand profiles

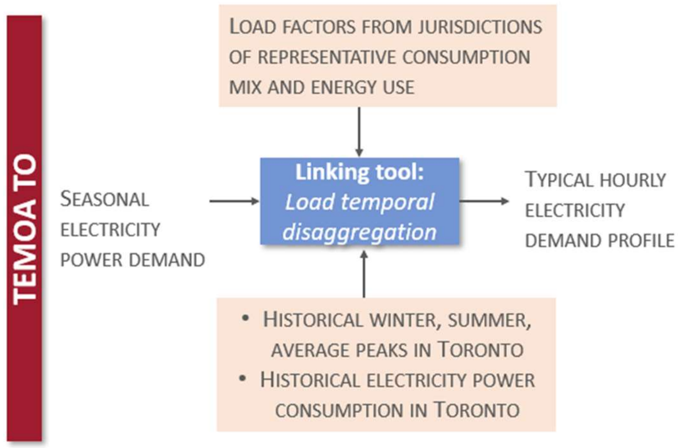


Table 19 provides the comparison of Toronto peaks and total consumption measured by Toronto-Hydro and calculated for SILVER-TO using the selected approach for several years. We consider that with the amount of available information regarding Toronto power system operation that required a range of assumptions and additional analysis, the difference in modelled peaks and total annual supply is acceptable. In the case that more information becomes available, the approach embedded in the Linking Tool may be adjusted leading to further decrease of the difference between modelled and measured data. Section 2.2.2 describes the way to change the hourly demand ratios used to recreate the load profile in the Linking Tool if needed.

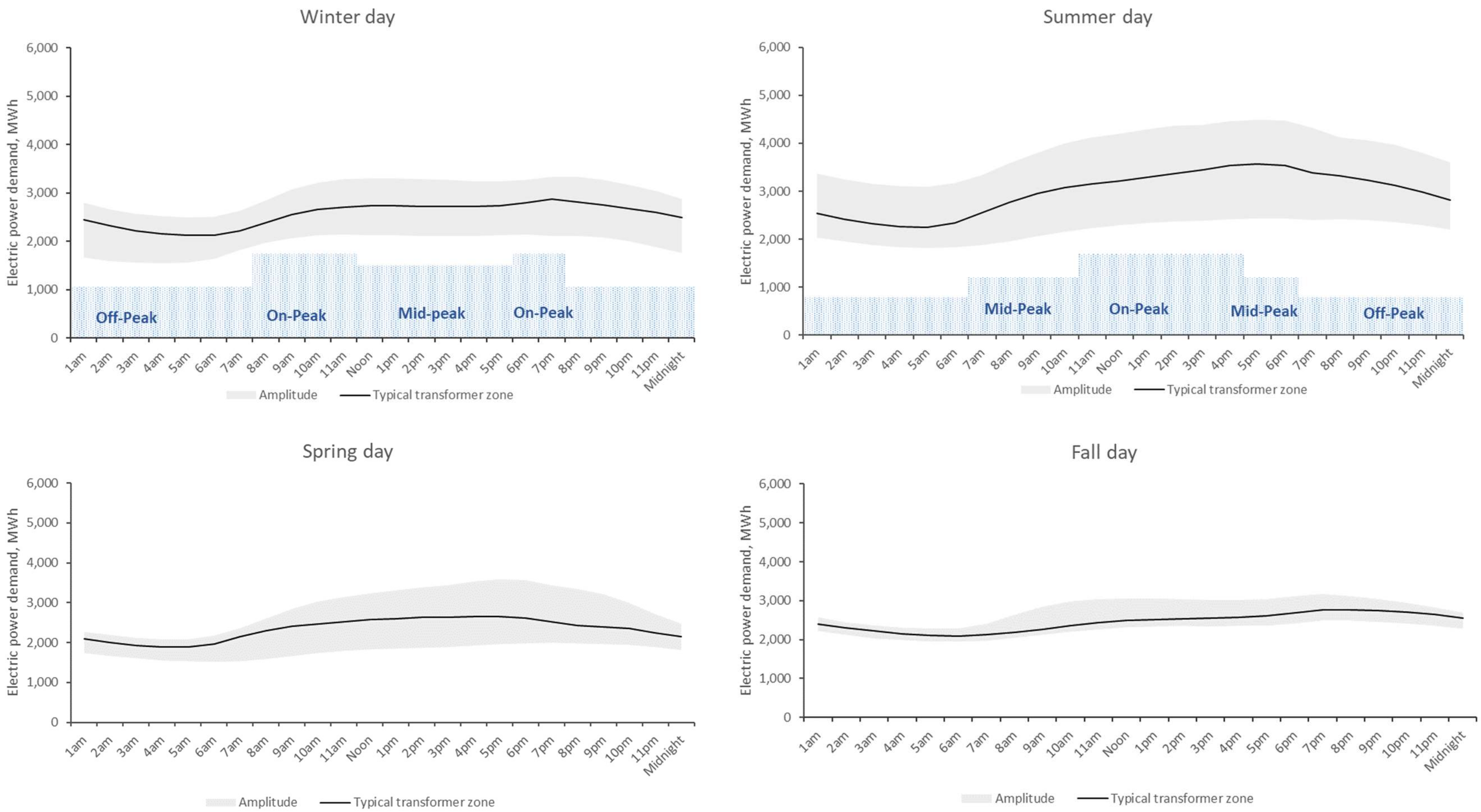
Table 19. Benchmark of modelled and measured parameters

	Parameters	Year		
		2018	2019	2020
SILVER-TO	Summer peak, MW	4,101	4,142	4,498
	Winter peak, MW	3,437	3,460	3,528
	Average peak, MW	3,602	3,633	3,802
	Annual supply, MWh	20,980,061	21,155,327	22,115,443
Toronto-Hydro	Summer peak, MW	4,560	4,272	4,493
	Winter peak, MW	3,799	3,917	3,511
	Average peak, MW	3,842	3,637	3,573
	Annual supply, MWh	24,678,859	23,859,235	23,137,481
Difference between modelled and measured parameter	Summer peak, %	-10%	-3%	0%
	Winter peak, %	-10%	-12%	0%
	Average peak, %	-6%	0%	6%
	Annual supply, %	-15%	-11%	-4%

The illustration of Toronto load profile using this approach is presented on Figure 45. These profiles consider electricity consumption may increase in the future due to various appliances electrification at the city level and it is assumed that this electrification will not affect the shape of the city load. The factors that will have the major impact on the city net load shape are available renewable (PV and wind) generation, electric vehicles (EV) charging demand, residential batteries charging/discharging dynamics and electricity generation from district combined heat and power (CHP). The effects of these factors will be automatically calculated by the Linking Tool based on the approaches described later in Section 2.1.3. Section 2.3 provides the overview of what Toronto city load may look like depending on:

- available renewable and district CHP capacities, batteries, and EV;
- technical specifications (e.g., efficiencies, watt peak, PV voltage and current, turbines cut-in and cut-off wind speeds) of various technologies;
- typical environmental conditions, such as hourly global horizontal irradiation (GHI), shading factors, temperature, and wind speeds in Toronto;
- typical consumer behaviour for residential batteries charging/discharging dynamics and EV charging strategies.

Figure 45. Result of temporal disaggregation for Toronto load profiles



2.1.3. Effect of distributed resources

Electrified new technologies and power generation systems will have significant impacts on the future total net load supplied by the grid in Toronto. This section describes how those impacts are modelled by the Linking Tool based on TEMOA-TO projections of installed capacities and technologies uses.

PV technologies

The hourly PV power generation profile is calculated from TEMOA output capacities and the generation potentials in the different areas of the city of Toronto during the day along the year.

GIS methodology for shading in dense city area

Hourly rooftop shading factors for Toronto were found using open data geographic information system (GIS) files and a free, open-source GIS software (QGIS). These data sources and software were chosen for ease of access and replicability of results. Required GIS input files were a digital surface model (DSM) in raster format[15] and building footprints in vector format[16]. An additional data file containing hourly solar azimuth and elevation was also needed[17]. The approach is described in more detail in ANNEX B.

The present approach was initially developed for the project of Regina (Saskatchewan)[18] and its methodology is similar to the one illustrated in Figure 46. For each postal code it is able to identify the available rooftop area, the average factor for solar shading, as well as to approximate a typical hourly PV power generation curve in different locations of Toronto.

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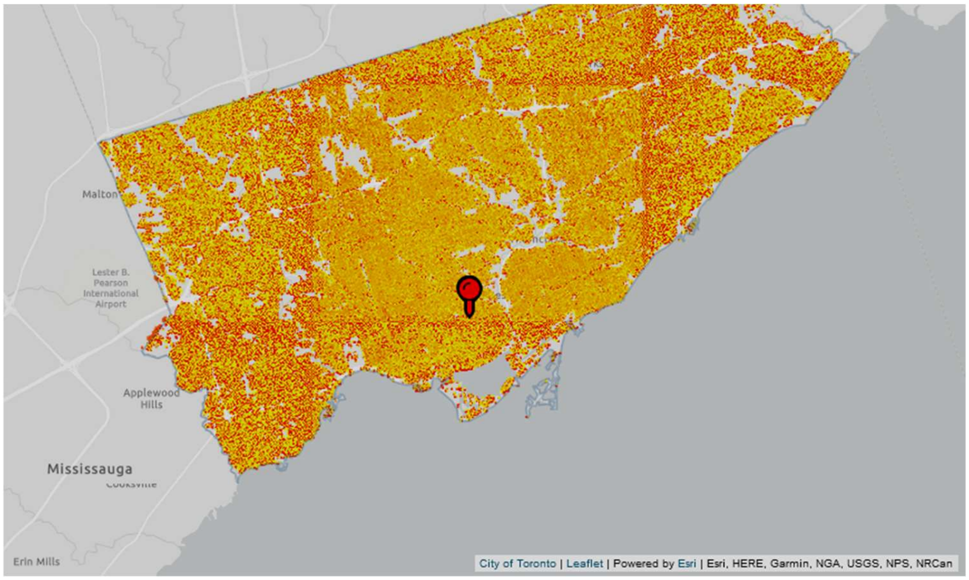
[15] NRCan - Natural Resources Canada (2021). High Resolution Digital Elevation Model (HRDEM) - CanElevation Series - Open Government Portal. Government of Canada. Online (Accessed in February 2023): https://open.canada.ca/data/en/dataset/957782bf-847c-4644-a757-e383c0057995

[16] City of Toronto (2022). Toronto - Open data catalogue. Online (Accessed in February 2023): https://open.toronto.ca/dataset/3d-massing/

[17] Global Monitoring Laboratory (2021). Solar Calculation Details. Online (Accessed in February 2023): https://gml.noaa.gov/grad/solcalc/calcdetails.html

[18] Dolter B. Seatle M. and M. McPherson (2023). When the Sun Sets on Net Metering: How the cancellation of Net Metering Impacted the Potential Adoption of Residential Rooftop Solar Photovoltaics in Regina, Saskatchewan. Under Rev. Challenges Sustain.

Figure 46. SolarTO Map of the city of Toronto[19]

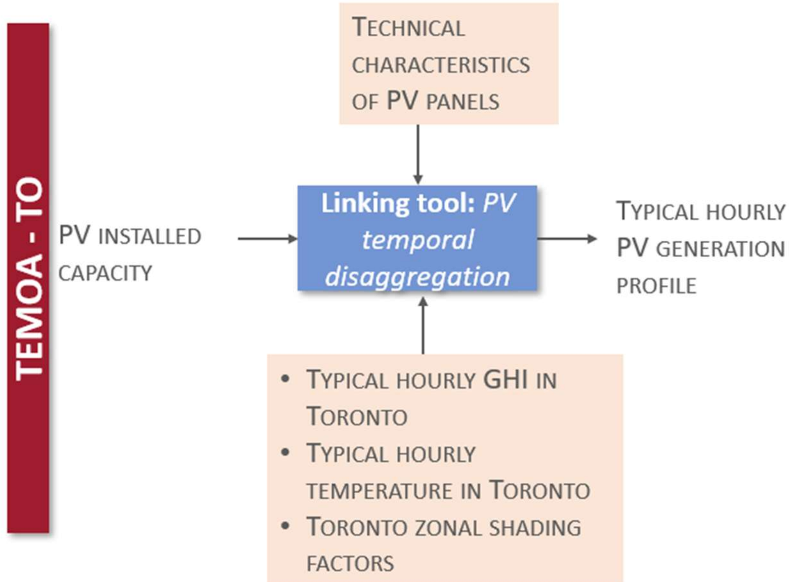


PV capacity disaggregation and power generation

TEMOA provides the total capacities per PV technology for the entire city. These capacities are disaggregated by transport zones and by transformer region proportional to the total electricity consumption in the region. This is made intentionally to represent in a more realistic way how PV distributed potential may grow in different Toronto zones (especially on private housing/commercial rooftops). The deployment of PV panels will not always be done based on the maximum solar potential, but will depend on various factors, such as the willingness of the building owner to invest in the distributed generation. A feedback loop based on zonal solar shading (ANNEX B) is used to ensure that the zonal installed capacities aren't greater than maximal zonal capacities (see section 2.2.2).

[19] City of Toronto (2023). SolarTO Map: SolarTO. Online (Accessed in February 2023): https://www.toronto.ca/services-payments/water-environment/net-zero-homes-buildings/solar-to/solarto-map/#location=&lat=&lng=

Figure 47. Schematic illustration of approach to calculate typical hourly PV generation profiles



To calculate typical hourly generation profiles of PV module in each transformer zone, the Linking Tool relies on the hourly GHI data for Toronto[20], technical characteristics of PV modules[21] and outdoor temperature to take into account a potential loss of module efficiency with the increase of ambient temperature[22] (Figure 47). More details regarding the calculation approach may be found in Atwa et al (2010)[23]. The Linking Tool automatically calculates PV generation profile for each transformer zone based on the installed capacity obtained from TEMOA-TO and the shading factor (Figure 49).The section 2.2.2 explains how to change or adapt any of those calculation parameters.

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[20] NRCan – Natural resources Canada (2023). Solar resource data available for Canada. Solar Photovoltaic Energy. Online (Accessed in February 2023): https://www.nrcan.gc.ca/energy/energy-sources-distribution/renewables/solar-photovoltaic-energy/solar-resource-data-available-canada/14390

[21] Sunceco (2021). Solar modules. Online (Accessed in February 2023): http://sunceco.com/solar-modules/

[22] Government of Canada (2023). Data download for Toronto. Online (Accessed in February 2023): https://toronto.weatherstats.ca/download.html

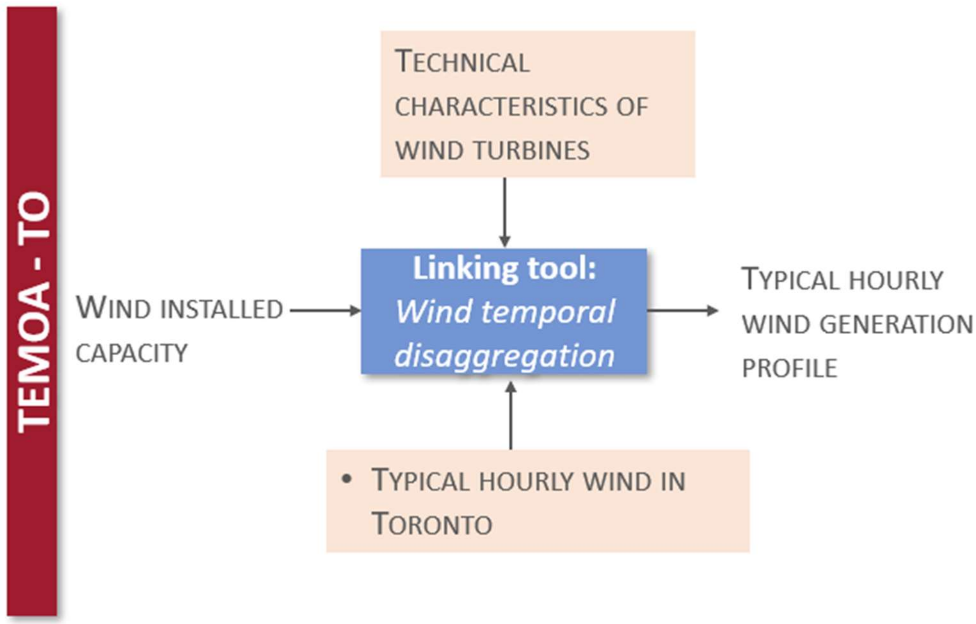
[23] Atwa Y. M. Salama M. M. A., and R. Seethapathy (2010). Optimal renewable resources mix for distribution system energy loss minimization. IEEE Trans. Power Syst. 25 (1): 360–370.

Kuznetsova E. and M. F. Anjos (2021). Prosumers and energy pricing policies: When, where, and under which conditions will prosumers emerge? A case study for Ontario (Canada). Energy Policy 149: 111982.

Wind technologies

Typical wind power generation profiles rely on the hourly wind speed profile in Toronto[24] and technical specification of wind turbine that may be installed in urban areas[25]. To calculate a typical wind power generation profile, a cubic approximation between an available wind speed, rated power and turbine characteristics was used[26] (Figure 48). Similar to PV, the Linking Tool automatically adjusts wind generation profile for each transformer zone based on the installed capacity extracted from TEMOA and disaggregated by transformer zone (Figure 49). The section 2.2.2 explains how to change or adapt any of the calculation parameters.

Figure 48. Schematic illustration of approach to calculate typical hourly wind generation profiles



Please note that the estimation of wind potential in dense urban areas is complex. Local wind characteristics, such as flow patterns, velocity, and turbulence intensity, are highly affected by building shapes and may significantly vary in different urban areas. In some cases, Computational Fluid Mechanics (CFD) simulation and field measurements (e.g., via ultrasonic anemometers and thermal flow velocity probes) may be required to validate wind turbine potential in an urban environment[27].

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[24] Government of Canada (2023). Data download for Toronto. Online (Accessed in February 2023): https://toronto.weatherstats.ca/download.html

[25] AEOLOS (2023). Aeolos Wind Turbine 1kW Specification. Online (Accessed in February 2023): https://www.windturbinestar.com/1kwh.html

[26] Sohoni V. Gupta S. C. and R. K. Nema (2016). A Critical Review on Wind Turbine Power Curve Modelling Techniques and Their Applications in Wind Based Energy Systems. *J. Energy*: 1–18.

[27] Juan Y. H. Rezaeiha A. Montazeri H. Blocken B. Wen C. Y. and A. S. Yang (2022). CFD assessment of wind energy potential for generic high-rise buildings in close proximity: Impact of building arrangement and height. Appl. Energy 321: 119328022.

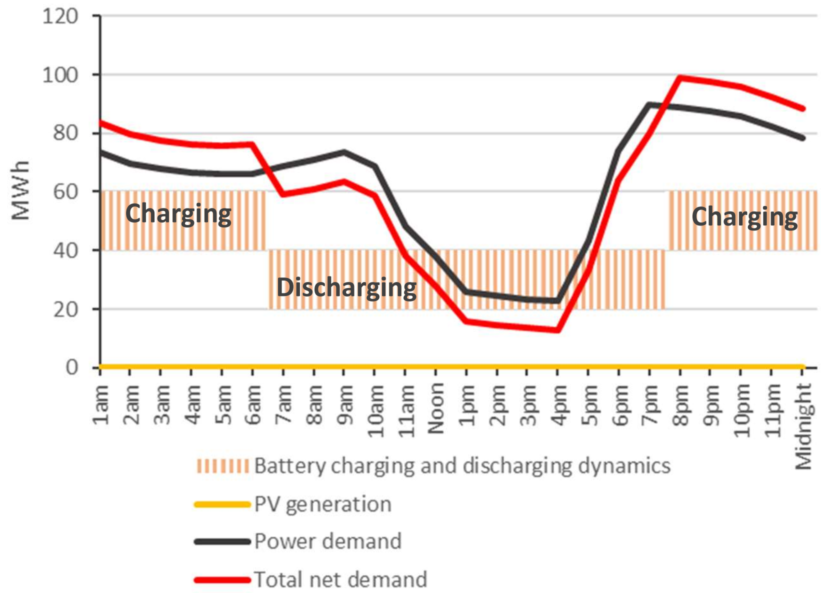
Figure 49. Example of temporal disaggregation of PV and wind. Generation profiles for 1,000 MW PV cumulated capacity and 200 MW wind cumulated capacity for several days in winter, spring, summer and fall in Toronto

Residential batteries

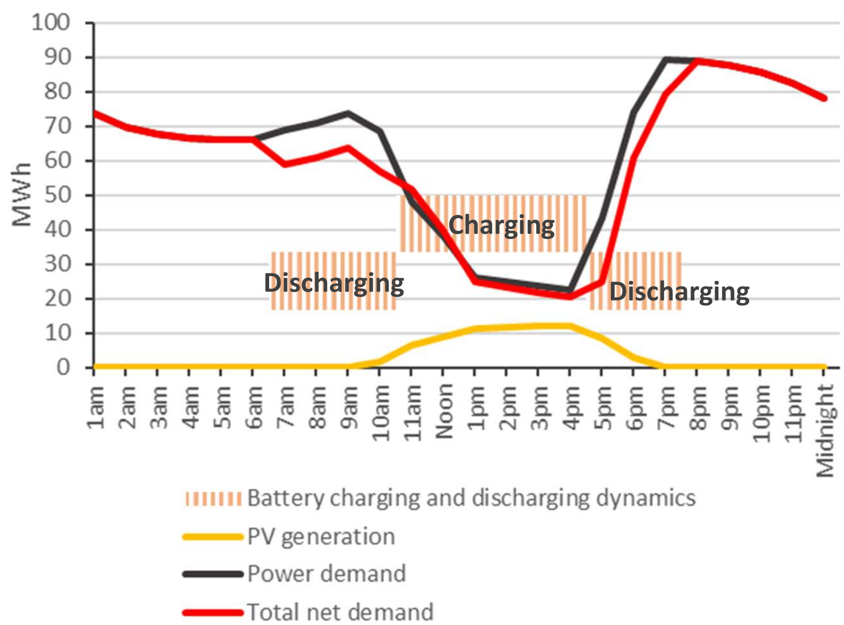
The management strategy for batteries, i.e., charging and discharging dynamics, also affects the total net load in each transformer zone. This strategy mainly depends on various factors related to the technology connection program, consumer reaction to the tariff price signal, consumer preferences in terms of technology management, etc. In general, two main charging and discharging behaviours may be distinguished (Figure 50):

- *Battery is charged from the grid during night hours and discharged during the day to decrease consumer electricity consumption from the grid.* This mode is typically associated with a consumer decision to install residential battery in a standalone mode (without PV) or when the PV panel capacity is small that does not allow (or make it interesting from the cost-saving point of view) to use PV generation for battery charging during the day.
- *Battery is charged during the day (mid-peak period) using PV power generation and during the night from the grid and discharged during two daily peaks.* This operation mode is common for the battery paired with PV panel which generation overcomes consumer load during hours or high solar irradiation typically coinciding with mid-peak period.

Figure 50. Schematic illustration of batteries charging/discharging dynamics during the day: a) charging with grid and b) charging with PV



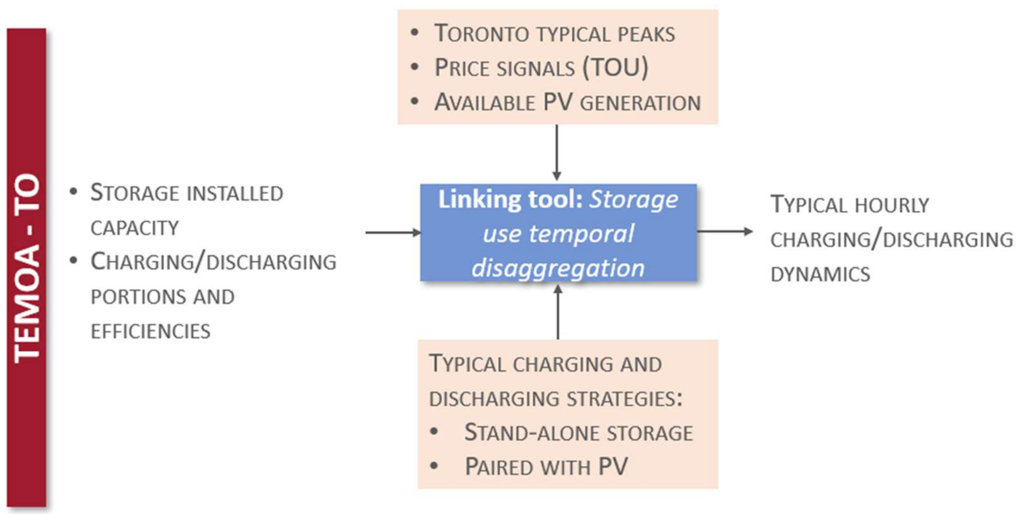
a)



b)

At the level of individual consumers battery management strategies may be different. The goal here is to capture the potential emergent worst-case scenario when one of the battery management strategies across large number of consumers may become dominant modifying total net load in a transformer zone. As it can be noticed, a particular charging and discharging dynamics may modify the shape of net demand to be supplied by the grid. Based on TEMOA outputs, the Linking Tool evaluates automatically available PV generation, storage capacity, and power to/from batteries at a city level and identifies the most likely battery management strategy that will be dominant among the city consumers (Figure 51). Details on this calculation and how to change parameters are provided in section 2.2.2.

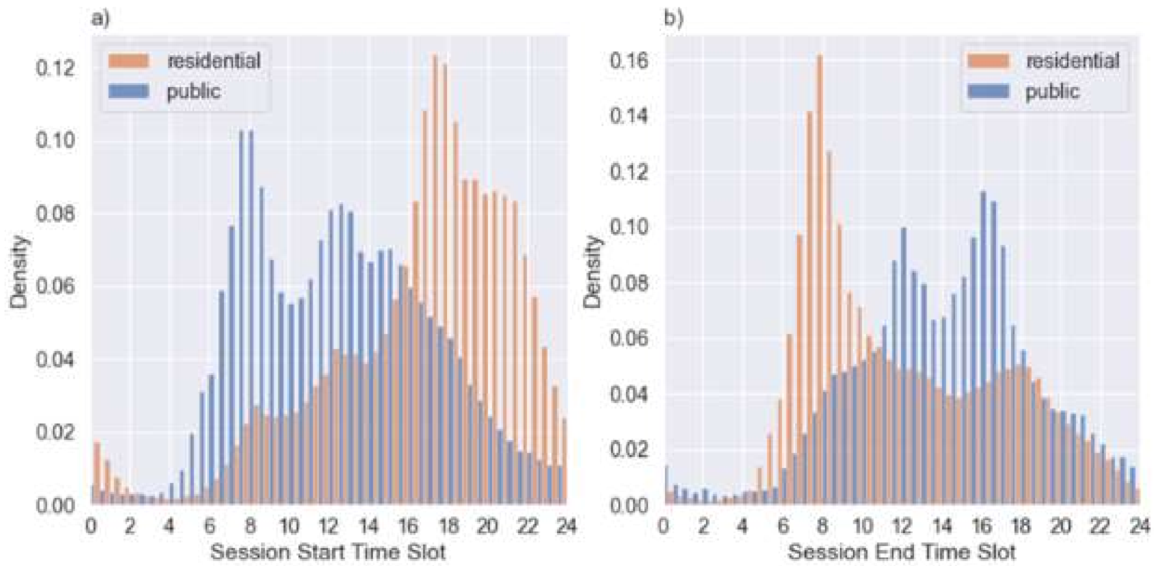
Figure 51. Schematic illustration of approach to calculate typical hourly storage charging/discharging dynamics



Electric Vehicles

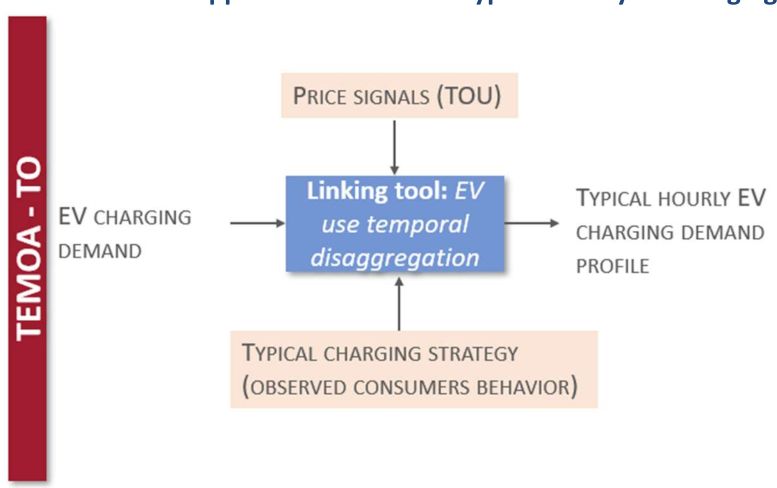
Typical hourly profile of electricity power demand due to EV charging was calculated based on the charging demand optimized with TEMOA and typical charging behaviour. Based on the study conducted for more than 7,000 charging stations in Canada, it was found that EV users start to massively plug-in their vehicles starting when their come home in evening (Figure 52). Charing EV at home is more frequent, it typically uses the time slot between 5 p.m. and 7 a.m. contributing mainly to the increase of evening peaks. EV charging in public charging station mainly occurs between 7 a.m. and 5 p.m. with the maximum load that may coincides with the mid-peak period in winter and peak period in summer.

Figure 52. Distribution of public and residential charging event counts over (a) session starts and (b) session ends[28]



Methodology to create typical hourly EV charging demand profile is presented in Figure 53.The information about the split between EV charging load in homes and public stations is coming from TEMOA but could be changed as explain in section 2.2.2.

Figure 53. Schematic illustration of approach to calculate typical hourly EV charging dynamics

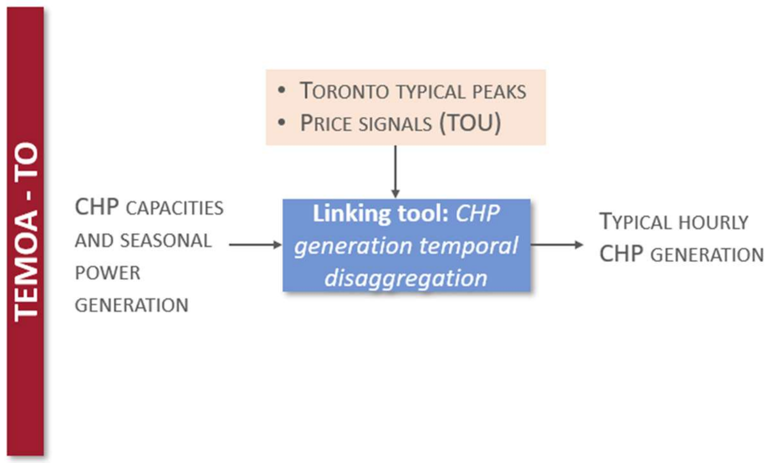


[28] Jonas T. Daniels N. and G. Macht (2023). Electric Vehicle User Behavior : An Analysis of Charging Station Utilization in Canada. Energies 16 (1592): 1–19.

Electric power generation with district CHP

District CHP is considered to be flexible on-demand electricity generation source. Therefore, its hourly generation profile may be established based on the Toronto needs, e.g., consumption peaks or periods of high demand (Figure 54). In the Linking Tool, this generation profile can be change as it is explained in section 2.2.2.

Figure 54. Schematic illustration of approach to calculate typical electric power generation with district CHP



2.2 How to use the Linking Tool ?

This section presents how to run the Linking Tool and how the change inputs parameters and internal characteristics of the model. Figure 55 and Figure 56 detail the structure of the Linking Tool folders and their files.

Figure 55. The Linking Tool main directory

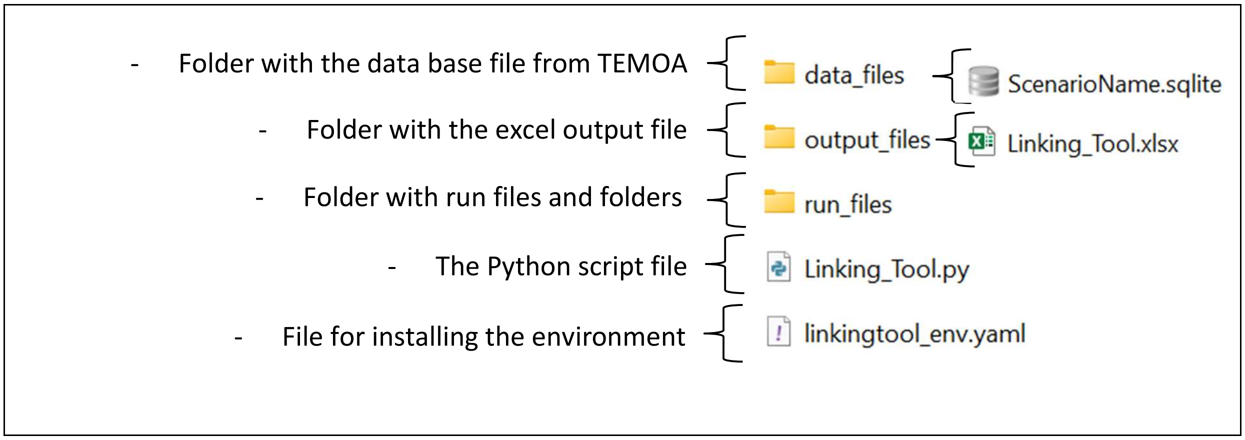
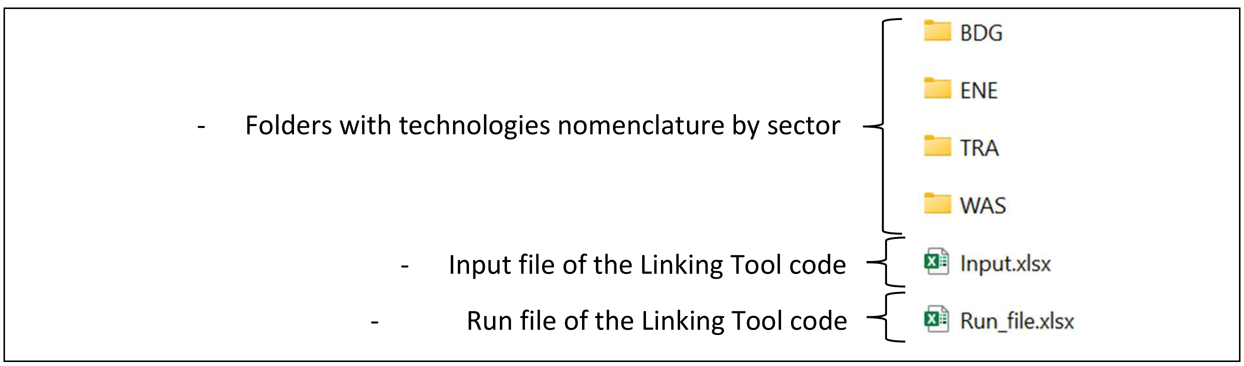


Figure 56. The Linking Tool *run_files* directory



2.2.1. Run the Linking Tool

Before running the model, make sure to download it and place it under the C drive. Moreover, it is recommended to avoid using any special characters or space in any folders or files name. All the files used in the Linking Tool must be closed before running it. The Linking Tool also automatically opens and closes excel workbooks to save modifications, so it is recommended to close the excel application and do not intervene if when the excel workbook is opening. Because the output excel file is quite big, this saving step may take minutes.

The creation of the Linking Tool environment is quick, but the run of the model can take around 15 minutes or more.

Install and set the Linking Tool

Download the code folder, unzip it, and place the folder under the C drive.

To run the model, open an Anaconda Prompt and enter the command from Figure 57 followed by enter. Note that the prompt after # are comments and not commands.

Figure 57. Creation of the environment of the Linking Tool

Anaconda Prompt

```
cd [path to the Linking Tool directory]

conda env create -f linkingtool_env.yaml #Create the environment

conda env list #Display the list of environments
```

If the environment is correctly installed, a line confirming the installation of linking_tool environment, and its location may appear on the anaconda prompt:

Figure 58. Environment installation check

```
(base) C:\Users\esmia>conda env list
# conda environments:
#
base                  *  C:\Users\esmia\anaconda3
linking_tool             C:\Users\esmia\anaconda3\envs\linking_tool
silver_env               C:\Users\esmia\anaconda3\envs\silver_env
temoa-py3                C:\Users\esmia\anaconda3\envs\temoa-py3
```

Open an Anaconda Prompt and enter the commands as per Figure 60 to activate the virtual environment.

Figure 59. Activate the Linking Tool environment

Anaconda Prompt

```
conda activate linking_tool #Activate the environment
```

Configure the scenario

Copy-paste the output SQLITE file generated by TEMOA-TO in the *TEMOA-TO/data_files* folder to the *Linking Tool/data_files* folder. Set the name of the input file in the 'Input' sheet of *Input.xlsx* from the *Linking Tool/run_file* folder (Figure 60).

Figure 60. Set the input database name

	A	B	C
1	DESCRIPTION		INPUT
2	db_file *without '.sqlite'*		NZ40
3			

Input | DO NOT CHANGE

The Linking Tool is currently designed to run with TEMOA using the advised temporal resolution presented in section 1.6.3 (with one year increment between 2016 and 2030 and then 5 years increment until 2050). If this temporal resolution is changed, the user will need to adapt the Linking Tool by modifying the sheet 'POP_TRZ_% ' in *Input.xlsx*, the sheet 'DO NOT CHANGE' in *Run_file.xlsx*, and a few lines of the code *Linking_Tool.py* as specified at the beginning of the main function.

Run the model

Open an Anaconda Prompt and enter the following commands to activate the virtual environment and then run the Linking Tool (Figure 61).

Figure 61. Run the Linking Tool

Anaconda Prompt

```
conda activate linking_tool #Activate the environment
cd [path to the linking tool.py directory]
Python Linking_Tool.py #Run the model
```

The results file is in *Linking Tool/output_files/Linking_Tool_.xlsx*. The data in this file will be used to configure SILVER as explained in section 3.3.2

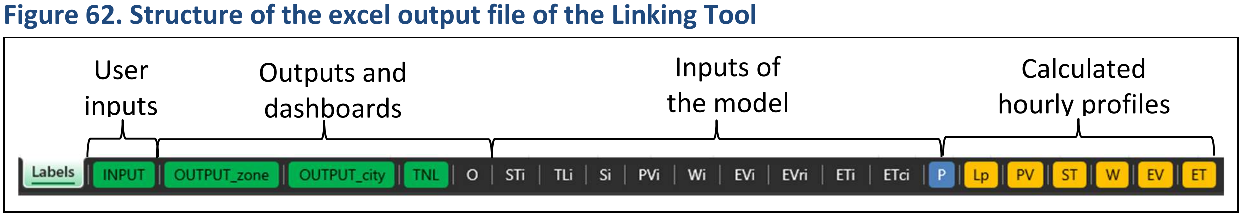
2.2.2. Configuration of internal parameters of the Linking Tool

The first part of the Linking Tool is the Python script. It reads the *Input.xlsx* file that contains the name of the database file of TEMOA and data from other sources used for the spatial disaggregation (e.g., population rate, shading factors…). Then, it executes SQL queries on the output database of TEMOA and writes down the results in *Run_file.xlsx*. Finally, it disaggregates the outputs of TEMOA from the city level to each transformer node and reports the resulting matrices in the excel output file (*Linking_Tool.xlsx* in *Output_files* folder). Based on those data, the excel output file of the Linking Tool does the second part of the Linking Tool by recreating the hourly total net load profile. The different methodologies and calculations to do so are provided in the following sections.

Structure of the excel output file

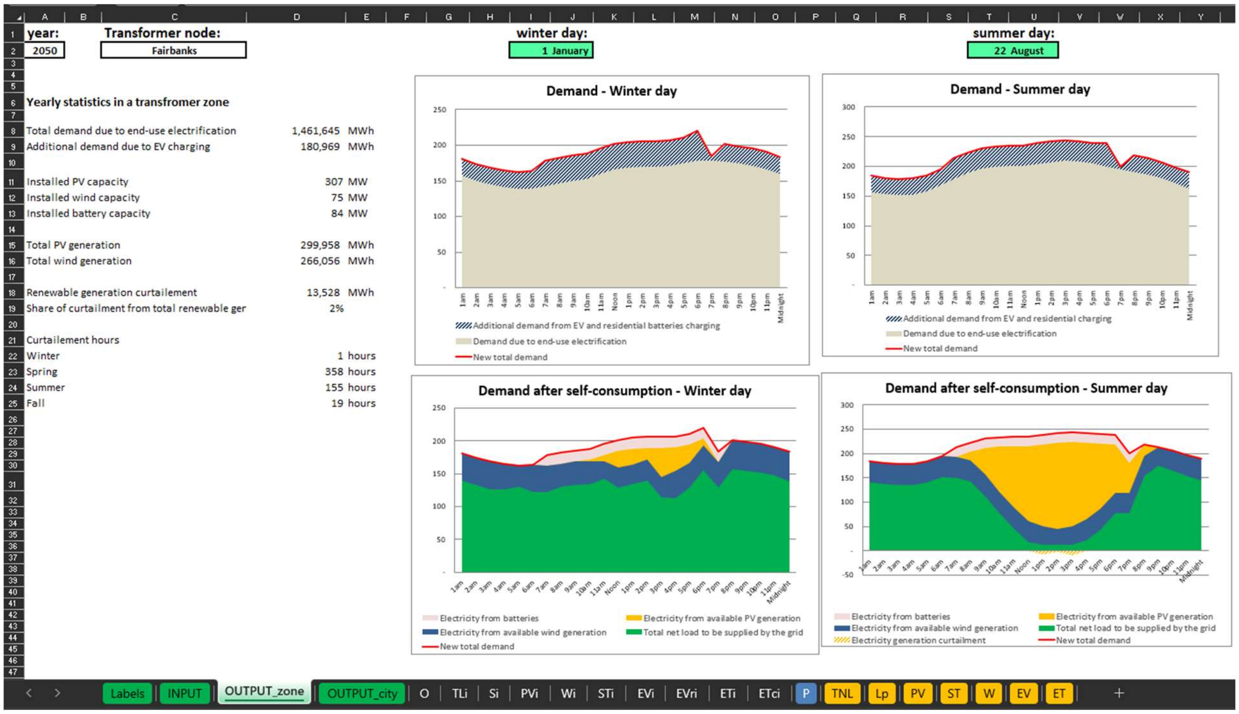
The output file of the Linking Tool contains yearly outputs of TEMOA and other inputs data by transformer nodes (sheets with name suffix i), hourly profiles calculated from the outputs of TEMOA by transformer nodes (yellow sheets), and inputs or outputs of the model (Figure 62). All sheets' descriptions are provided in sheet 'Labels'.

Figure 62. Structure of the excel output file of the Linking Tool



Outputs of the model are the total net load for SILVER-TO (in sheet 'TNL') and the two dashboards: one for a specific transformer node and the other one for the whole city of Toronto. It shows for a specific day in Summer and in Winter, the demand supplied by the grid and how new electrical technologies and power generators affect this load. The two input days can be changed, and graphs will be updated based on data in the 'O' sheet. However, the name of the transformer node is only indicative. For a time consuming issue, to generate the results for an other transformer, the formulas in sheet "O" may be manually modified and it will automatically update the graphs and metrics in "Output_zone".

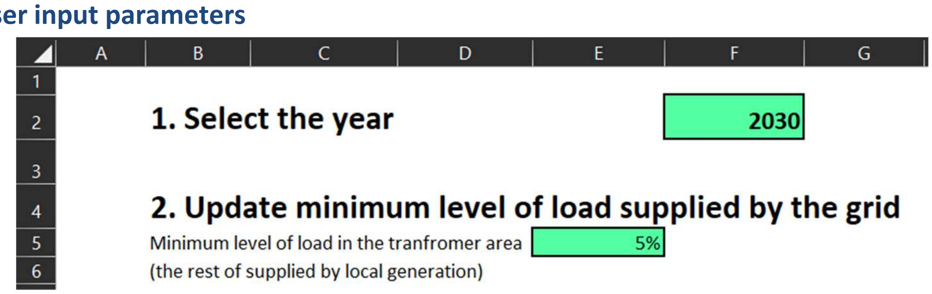
Figure 63. Dashboard of the Linking Tool results



Input parameters

The 'INPUT' sheet selects the year calculated by the Linking Tool (Figure 64). It affects all the calculation of the spreadsheet so changing its value can take a few minutes to update. In this sheet, the minimum level of load supplied by the grid (percentage) and not by local generation can be input. The other inputs are used for power generation or charging/discharging strategies and will be discussed in the sections below.

Figure 64. User input parameters



Power demand profile

As explained in the section 2.1.2, the hourly load profile is calculated based on a data intensive study on New York City. The hourly demand ratios of this study are provided in the sheet 'P' and used to calculate the load profile of sheet 'Lp' by multiplying it by the seasonal total load of TEMOA from sheet 'Tli'.

PV and wind turbine generation

To create the hourly power generation profile from PV panels or wind turbines(see section 2.1.3), the user can input the technical characteristics of the technologies (see Figure 65). Other parameters affecting the power generation such as hourly temperature, GHI or wind speed can be modified in the 'P' sheet in PV and wind turbines generation sections. The power generation of renewable sources is also mitigated by constraint factors by transformer nodes for wind turbines and average solar shading for PV panels (Sheet 'Si'). Specifically for PV generation, the model uses the total rooftop areas available by transformer nodes to verify that the capacities provided by TEMOA aren't greater than capacities available. If needed, it redistributes capacities in other transformer nodes to comply on maximum available capacities. Based on all those data and the verified capacities installed per year (Sheets 'PVi' and 'Wi'), the Linking Tool calculates the hourly power generation for the modelled year respectively in sheets 'PV' and 'W'.

Figure 65. User input technical characteristics of renewable power generation sources

	A	B	C	D	E	F	G	H	I	J
8		3. Update renewable technolgies specification								
9										
10		PV module					Wind turbine			
11		Watt peak, W			300		Rated power, W			1000
12		Open circuit volt, V			44.71		Rated wind velocity, m/s			12
13		Short circuit current, A			8.947		Cut-in wind velocity, m/s			2.5
14		Voltage at maximum power, V			37.23		Cut-off wind velocity, m/s			45
15		Current at maximum power, A			8.06					
16		Voltage temperature coef, V/C			-0.152014		Cubic approximation			
17		Current temperature corf, A/C			-0.0044735		a			0.583984
18		Nominal operational temp, C			47		b			1.009125
19		Module temperature at STC, C			25					
20										
21		Fill factor			0.750146299					
22										
23		Additional information:								
24		Monocrystalline cell								
25		Dimension, mm			2078 * 992 * 35					
26		surface, m2			2.061376					

Residential storage charging/discharging dynamics

As explain in section 2.1.3, residential storage technologies can be charge from PV generation or from the grid. To model the predominant user behaviours, the user can choose the daily charging and discharging dynamics of the residential storages in the input sheet of the Linking Tool (Figure 66).

Figure 66. User inputs technologies usage dynamics

4. Update technologies usage dynamics (e.g., based on consumers behavior)

	Residential storage		EV		District CHP
	Charging from grid	Charging from PV	Charing in homes	Charging in public stations	
1am	CH	-	CH	USE	GEN
2am	CH	-	CH	USE	GEN
3am	CH	-	CH	USE	GEN
4am	CH	-	CH	USE	GEN
5am	CH	-	CH	USE	GEN
6am	CH	-	CH	USE	GEN
7am	DIS	DIS	USE	CH	GEN
8am	DIS	DIS	USE	CH	GEN
9am	DIS	DIS	USE	CH	GEN
10am	DIS	DIS	USE	CH	GEN
11am	DIS	CH	USE	CH	GEN
Noon	DIS	CH	USE	CH	GEN
1pm	DIS	CH	USE	CH	GEN
2pm	DIS	CH	USE	CH	GEN
3pm	DIS	CH	USE	CH	GEN
4pm	DIS	CH	USE	CH	GEN
5pm	DIS	DIS	USE	CH	GEN
6pm	DIS	DIS	CH	CH	GEN
7pm	DIS	DIS	CH	USE	GEN
8pm	CH	DIS	CH	USE	GEN
9pm	CH	-	CH	USE	GEN
10pm	CH	-	CH	USE	GEN
11pm	CH	-	CH	USE	GEN
Midnight	CH	-	CH	USE	GEN

In sheet ‘ST’, from the PV power generation and the load profiles, the Linking Tool calculates excess PV generation corresponding to the available charging power per transformer nodes. In parallel, it calculates the maximum total charging power per transformer nodes based on the installed capacities from TEMOA. It compares those two values and decides if the residential storage will be charging from the grid or from PV generation during the year. For both solutions, it follows the input strategy. It finally gives the hourly charging and discharging profiles during the year per transformer nodes.

Electric vehicles charging

As for the residential storage, the user input the charging strategy by station types(see Figure 66). Here, the Linking Tool calculates, from TEMOA outputs (sheets ‘EVi’ and ‘EVri’), the share of charging load by station types (public station or at home). Then, it recreates the hourly charging load profiles at public station and at home per transformer nodes based on the inputted charging strategy (sheet ‘EV’).

District CHP

In the input sheet, the user can choose the moment of the day when the district CHP are generating power (see Figure 66). Then, from the output capacities or seasonal power generation of TEMOA (sheet ‘ETi’), the model is able to recreate the hourly power generation profile of district CHP for the year studied (in sheet ‘ET’).

Calculation of the Total net Load

The total net load is calculated in sheet ‘TNL’ from all the other hourly load or generation profiles as explained in section 2.3. The model is constrained to comply with the minimum percentage of load supplied by the grid provided by the user in the ‘INPUT’ sheet.

Changing the spatial disaggregation of the Linking Tool

The Linking Tool is specifically designed to disaggregate data from TEMOA-TO down to the level of transformer nodes. However, it can also be applied to other levels of disaggregation with some necessary adaptations. To utilize the tool at a different scale, adjustments would be required for the input parameters and the structure of the Linking Tool. Proficiency in Python programming and understanding of the integration with Excel worksheets are essential.

To begin with, the user would need to create a matrix in the Input.xlsx file that corresponds to the desired spatial disaggregation and replace any existing matrices with outdated information. For instance, if the user intends to replace population data by traffic zones with population data by wards, almost all the sheets containing data in the Input Excel file would need to be substituted, excluding the "Solar_Shading_area_available" sheet. In the Python script, the section responsible for generating the matrices used in the linking tool, where TEMOA-TO's outputs are multiplied by the relevant disaggregation matrices, would need to be modified to accommodate the new disaggregation scale. This might involve altering the length or names of the matrices. Finally, in the output file of the Linking Tool, all calculation and output sheets would need to be adjusted to fit the new disaggregation scale, which typically involve modifying the yellow and green sheets.

2.3 Results overview and interpretation

Net load is defined as the power demand (load) minus generation from variable renewable generation, electricity used from the batteries, plus electricity used to charge batteries and EV. The example of how various technologies and their use may affect the total net load is presented on Figure 67 and Figure 68. Please note that at this point results in this section are provided for illustration purposes and may not entirely reflect a particular scenario analyzed with TEMOA.

As it can be observed, a future resulting net load profile may be highly impacted by distributed generation, storage, and EV, creating important ramp-up and ramp-down effects and accentuating peaks. These changes in net load that needs to be supplied by the grid may create particular risks for the provincial power transmission and generation infrastructure. To mitigate these risks different actions can be taken at the level of the city, and transmission and generation infrastructure. For example, at the city level these load variations may be balanced by flexible resources, such as dispatchable power plants (district CHP), changing charging/discharging dynamics at the consumer levels or the increase in demand response participation in order to maintain system stability.

In this specific example, in 2030 demand due to EV charging is almost not noticeable in Figure 67. The major impact to the total net load shape is coming from renewable generation. PV generation at a city level may start to reshape the total net load as a duck belly.

By analyzing resulting profiles in 2050 on Figure 68 together with yearly statistics in Table 20 the following may be noticed:

- Important “Duck curve” effect for summer days due to important PV power generation at the city level;
- Sensible net load variation due to the wind power generation at the city level;
- Curtailment of renewable generation (almost all is related to PV) especially during the summer days.

Already at the level of Linking Tool, the User may identify some potential solutions to mitigate these effects:

- increase residential storage capacity at a city level (policy to be tested in TEMOA).
- stimulate different charging/discharging behaviour so batteries will be charged during the day reducing Duck curve and discharging during the night to decrease the difference between night and day periods (behaviour may be updated in Linking Tool, but incentive must be studied with some appropriate tool representing individual consumer behaviour under different incentives and prices).
- use district CHP (not shown at these figures) to generate most of electricity during high demand periods to smooth net load variations and to decrease ramps.

Detailed analysis of net load effect on the transmission system, associated risks and potential mitigation actions could be done based on SILVER-TO results (see section 3.4 below).

Figure 67. Example of total net load construction for a transformer zone for year 2030

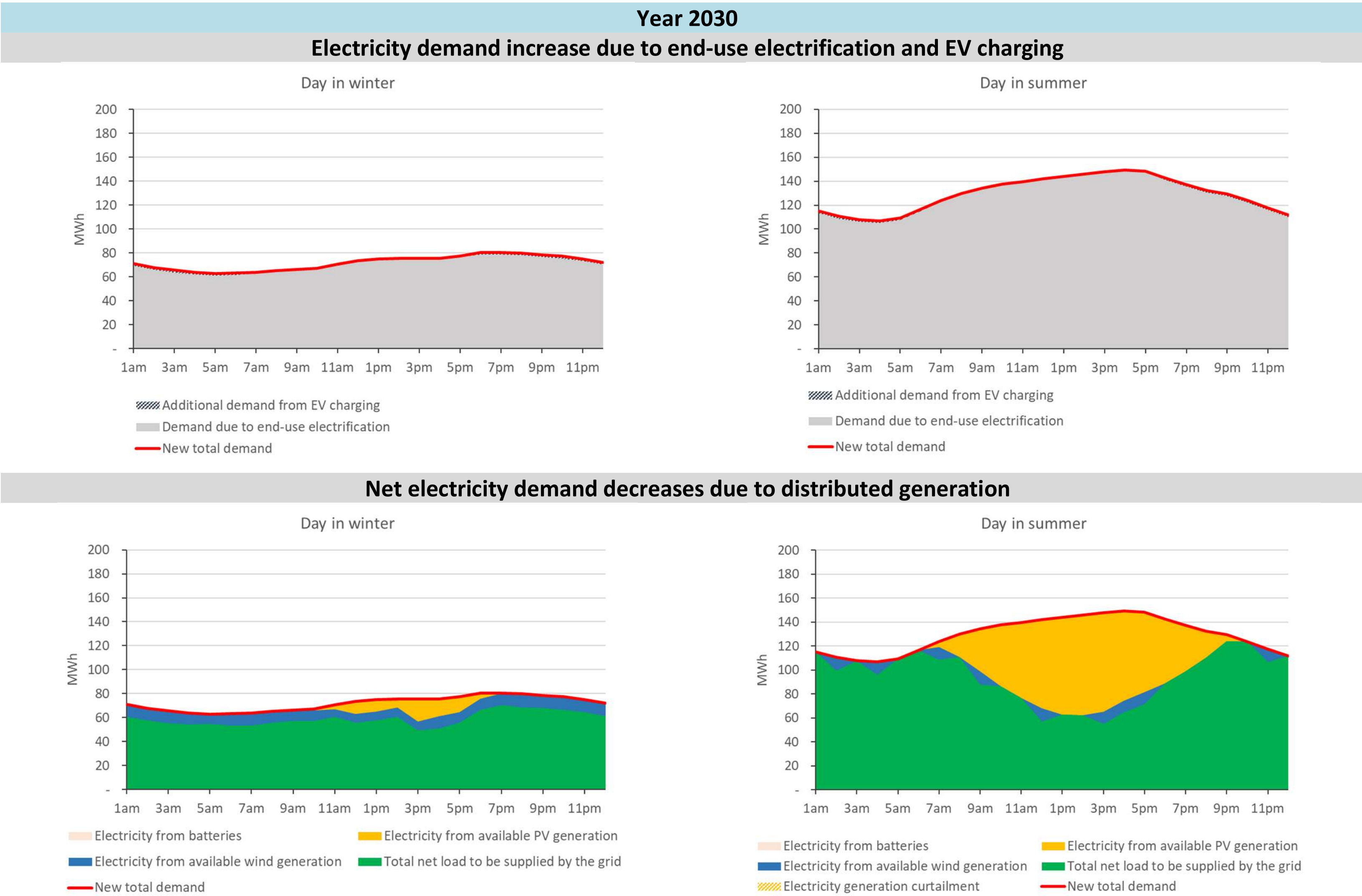


Figure 68. Example of total net load construction for a transformer zone for year 2050

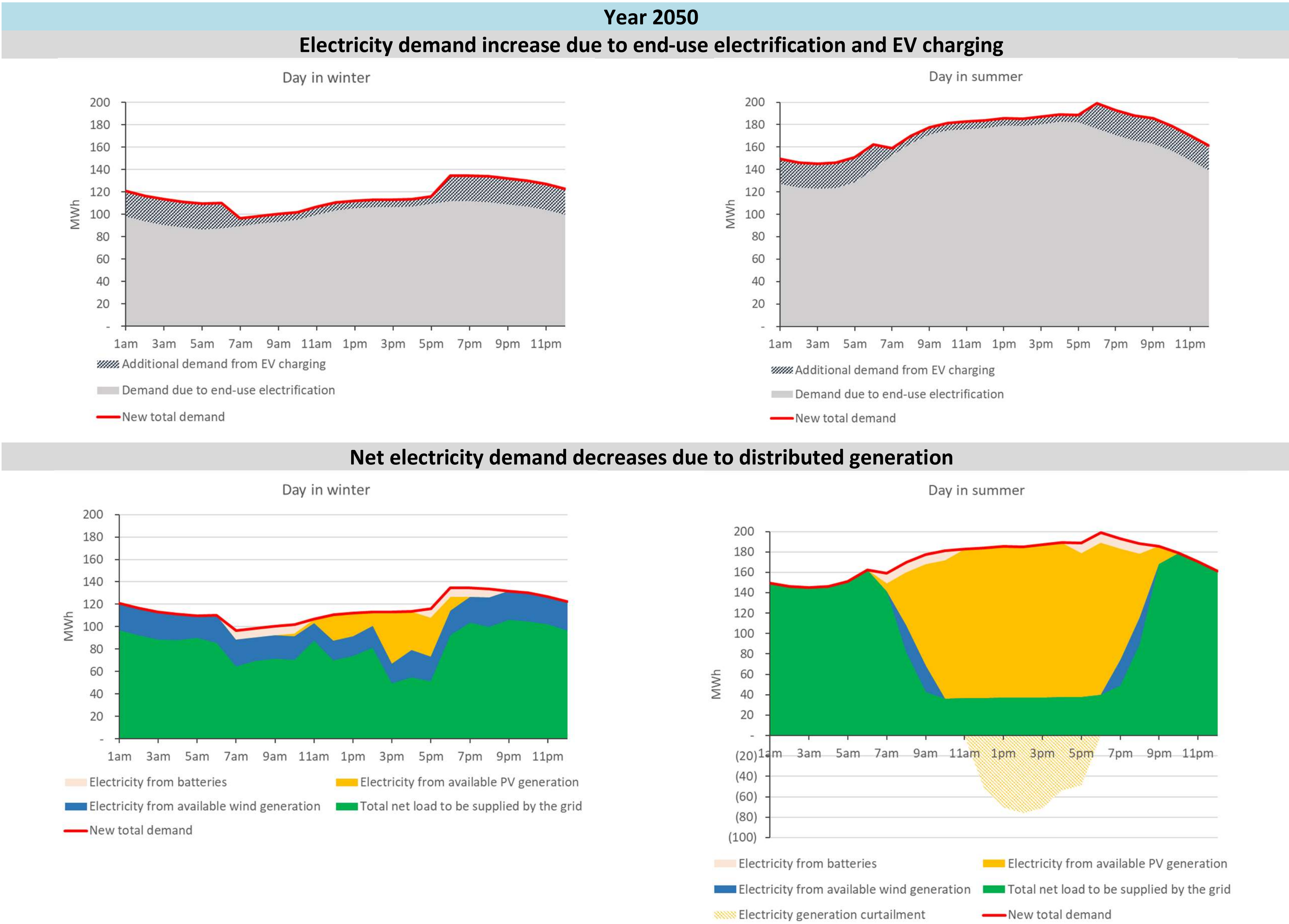


Table 20. Example of yearly statistics for the same transformer zone

Parameters	Unit	Year	
		2019	2020
Electric power demand			
Total electric power demand due to end-use electrification	MWh	764,977	1,028,609
Additional demand due to EV charging	MWh	10,480	134,504
Installed capacities			
PV generation capacity	MW	134	377.9
Wind generation capacity	MW	18.2	43.9
Total capacity of distributed batteries	MW	1.4	22.16
Renewable generation			
Total PV generation	MWh	130,829	368,932
Total wind generation	MWh	65,048	156,813
Renewable generation curtailment			
Curtailed distributed generation	MWh	2,378	56,185
Share of curtailment from total renewable generation	-	1%	11%
Number of hours with generation curtailment by season			
Winter	h	161	52
Spring	h	-	532
Summer	h	-	268
Fall	h	-	95

3. SILVER-TO

SILVER-TO focuses on grid-operator scale and is used to evaluate the impact of a Toronto energy transition (such as electrification of end-use appliances, deployment of renewable generation, such as PV and wind, etc.) on the transmission power system. Power transmission system inside Toronto corresponds to 115 kV and 230 kV transmission lines.

The original SILVER model was developed by researchers from the Sustainable Energy Systems Integration & Transitions (SESIT) Group at the University of Victoria. The tool was used in various projects, such as electricity grid design for high intermittent renewable resources penetration for Ontario[29] and the City of Regina[30], deploying storage assets to facilitate variable renewable generation[31] integrating EV with variable renewable generation under differing degrees of decentralization[32], and analyzing flexibility of the Canadian electricity system in a zero emission electric grid[33]. The problem solved by SILVER is a mixed integer linear program (MILP) model whose objective function is to minimize the cost while still respecting several operational constraints, including generators, loads, and network constraints[34]. The objective function minimizes system cost by considering generator operation costs. The network constraints include the: maximum flow of line, voltage angle of substation, and power balance constraint. In general, SILVER account for the following generators constraints: maximum and minimum output power, maximum ramp up/down, minimum up/down time, availability of water in reservoir (for hydro generation), and water balance between reservoirs (for cascading hydro generation). For the project, SILVER-TO keeps some of these constraints in the script, in light of potential model expansion (to consider not only Toronto, but also partly or entirely provincial system), but did not use them for Toronto transmission system optimization.

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[29] McPherson M. and B. Karney (2017). A scenario based approach to designing electricity grids with high variable renewable energy penetrations in Ontario, Canada: Development and application of the SILVER model. Energy 138: 185–196.

[30] Dolter B. Seatle M. and M. McPherson (2023). When the Sun Sets on Net Metering: How the cancellation of Net Metering Impacted the Potential Adoption of Residential Rooftop Solar Photovoltaics in Regina, Saskatchewan. Under Rev. Challenges Sustain.

[31] McPherson M. and S. Tahseen (2018). Deploying storage assets to facilitate variable renewable energy integration: The impacts of grid flexibility, renewable penetration, and market structure. Energy 145: 856–870.

[32] McPherson M. Ismail M. Hoornweg D. and M. Metcalfe (2018). Planning for variable renewable energy and electric vehicle integration under varying degrees of decentralization: A case study in Lusaka, Zambia. Energy 151: 332–346.

[33] Miri M. Saffari M. Arjmand R. and M. McPherson (2022). Integrated models in action: Analyzing flexibility in the Canadian power system toward a zero-emission future. Energy.261, no. PA: 125181.

Saffari M. and M. McPherson (2022). Assessment of Canada’s electricity system potential for variable renewable energy integration. Energy 250: 123757.

[34] McPherson M. and B. Karney (2017). A scenario based approach to designing electricity grids with high variable renewable energy penetrations in Ontario, Canada: Development and application of the SILVER model. Energy 138: 185–196.

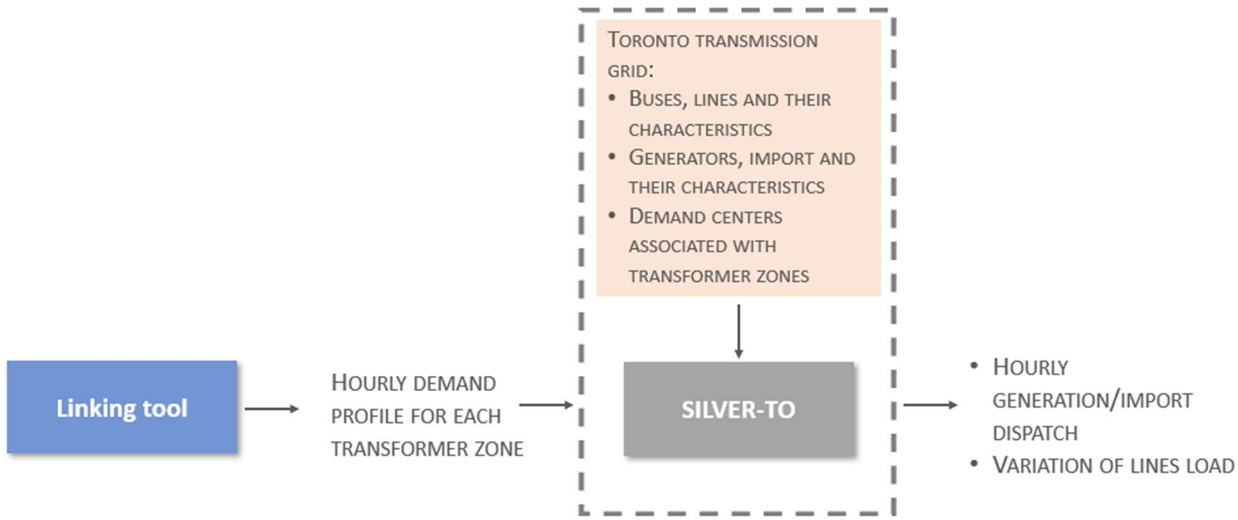
The SILVER-TO model comprises three modules:

- the day-ahead network-constrained price-setting dispatch that optimizes the 24-h day ahead economic dispatch solves for the network-constrained system marginal price based on demand and available power generation;
- the day-ahead unit commitment that minimizes the daily system costs over an entire 24-h period by imposing additional optimization constraints that are discussed below, but excluding transmission constraints; and
- the real-time optimal power flow dispatch that solves the optimal power problem by considering power flow and other operational constraints.

At the last stage, the model may also adjust generation units' commitment depending on the difference between forecasted and real load. This functionality, however, is less pertinent for Toronto since almost all generators fall outside of the city perimeter.

SILVER-TO relies entirely on SILVER source code with the input representing Toronto transmission system (Figure 69).

Figure 69. Schematic illustration of SILVER-TO inputs and outputs



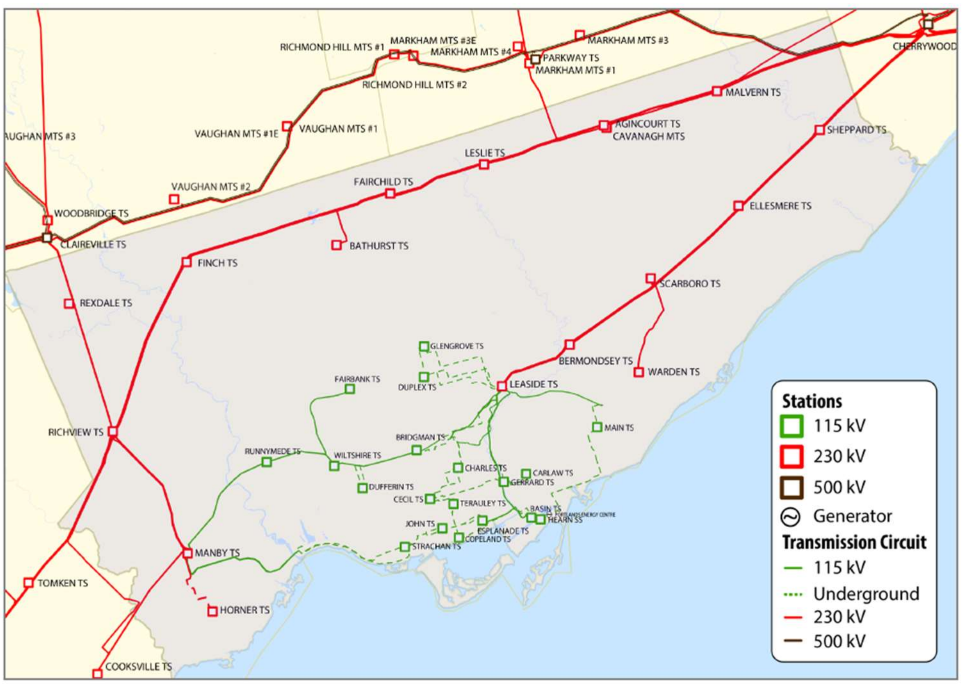
3.1 Toronto power grid

Toronto transmission system and its detailed electrical scheme are presented in Figure 70 and Figure 71, respectively [35].

Table 21. Toronto transmission station facilities[36]

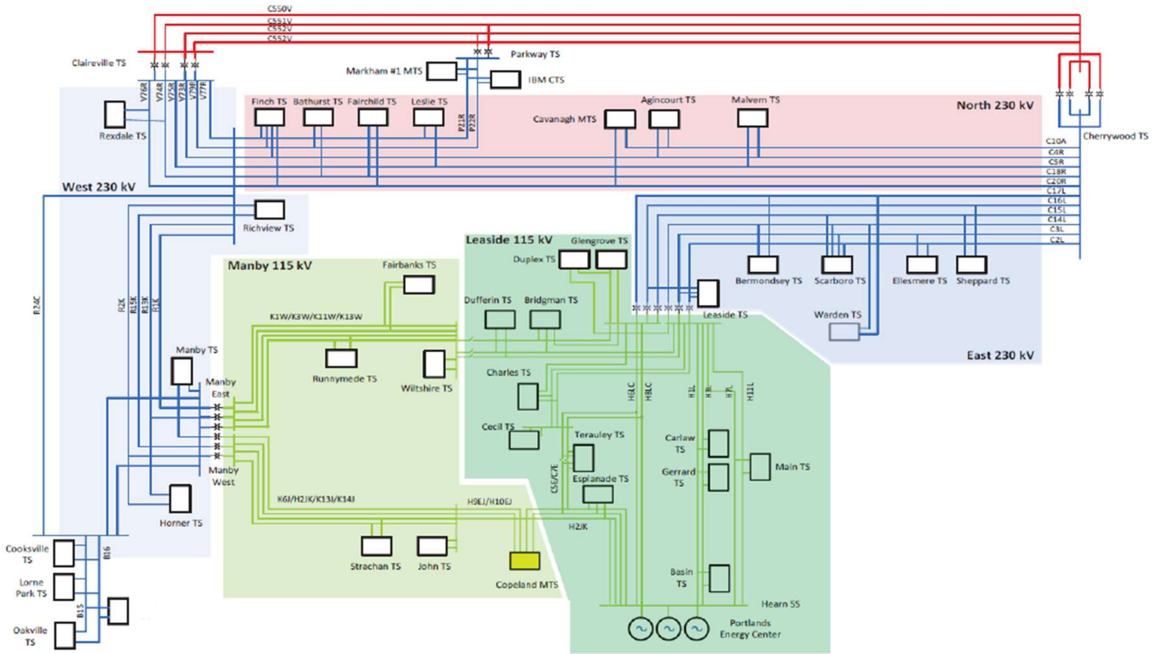
Leaside 115 kV	Manby 115 kV	East 230 kV	North 230 kV	West 230 kV
Basin TS	Copeland TS	Bermondsey TS	Agincourt TS	Horner TS
Bridgman TS	Fairbanks TS	Ellesmere TS	Bathurst TS	Manby TS[3]
Carlaw TS	John TS	Leaside TS[4]	Cavanagh TS	Rexdale TS
Cecil TS	Runnymede TS	Scarboro TS	Fairchild TS	Richview TS
Charles TS	Strachan TS	Sheppard TS	Finch TS	
Dufferin TS	Wiltshire TS	Warden TS	Leslie TS	
Duplex TS			Malvern TS	
Esplanade TS				
Gerrard TS				
Glengrove TS				
Main TS				
Terauley TS				
Hearn SS[5]				

Figure 70. The regional transmission system supplying Toronto



[35] IESO - Independent Electricity System Operator (2019). Toronto Region: Integrated Regional Resource Plan.
[36] IESO - Independent Electricity System Operator (2019). Toronto Region: Integrated Regional Resource Plan.

Figure 71. The Toronto region electrical system (single-line diagram)



The Toronto transmission system is subdivided into 5 zones (Table 21): 17 transformer stations (TS) and 16 major circuits at the 230 kV level, and 19 TS and 35 major circuits at the 115 kV level. Each circuit is composed of several power lines, so transmission nodes inside Toronto are connected to more than 100 lines in reality (according to the Canadian Open-source Database for Energy Research and Systems Modelling (CODERS) database[37]).

The Toronto power grid includes one gas plant, Portland Energy Center, connected at a transmission level at Hearn switching station (SS). This power plant is managed by the Independent Electricity System Operator (IESO) within the Ontario generation portfolio to address provincial electricity power demand.

[37] Hendriks R. M. Jurasz J. Cusi T. Aldana D. Monroe J. Kiviluoma J. and M. McPherson (2021). CODERS : Introducing an open access dataset for decarbonizing Canada's energy system.

3.2 SILVER-TO model input overview

Based on the original SILVER model, the SILVER-TO model was developed in order to represent the Toronto power grid. In the following sections, only inputs adapted to the Toronto model are described. Further information is provided in SILVER's documentation[38].

3.2.1. Grid architecture

To ensure computational tractability of the Toronto case, SILVER-TO relies on the adapted network topology built using specific rules for power system adaptation. Figure 72 exemplifies some of these rules. For example, the elimination of tap[39] leads to a less complex grid version that may significantly decrease calculation time while still providing realistic results.

The resulting Toronto transmission system modelled with SILVER-TO is illustrated in Figure 73. Each connection is characterized through:

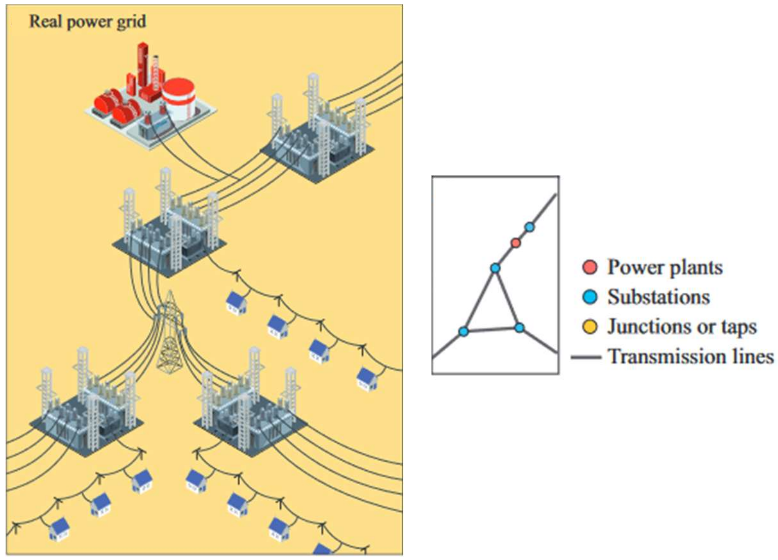
- TS or buses of start and end;
- voltage level;
- connection length calculated based on the geographical locations (longitudes and latitudes) of TS using the approach to compute distance between points with geographical coordinates and adjusted with coefficients for not straight connections;
- maximum line capacity (i.e., maximum power that each line is able to transmit);
- line reactance measuring the opposition that electronic components exhibit to a change in current.

In theory, transmission lines' characteristics do not require modification from the model user. However, due to the limited data on the transmission system in general that led to different assumptions, the user has the possibility to update the network configuration and technical specification if additional information becomes available.

[38] SESIT – Sustainable Energy Systems Integration and Transitions group (2022). Strategic Integration of Large-capacity Variable Energy Resources (SILVER): User Manual. Online (Accessed in February 2023): https://gitlab.com/McPherson/silver/-/blob/1cd92368eb12beaeaf61a5aed092b4321b6e3429/SILVER%20-%20User-manual%20-%20Open%20Access%20Version%20-28%20NOV%202022.pdf

[39] Tap connection is a short extension line from a facility to the main grid.

Figure 72. Conversion schemes from a power grid to a network topology[40]



3.2.2. Power generation

SILVER-TO handles generation technologies depending on the level of the grid where the generator is connected:

- If a centralized generator is connected at a grid operator level (>115 kV), the model represents generation technologies as individual production units that are modelled to follow operational constraints. In this case, details regarding generator location, capacity, typical generation profile (if it is intermittent generation source) must be specified in input sheets. In the output, the model provides a solution for units (generators) commitment showing the participation of each generator to ensure supply-demand adequacy. In doing so, the model allows to validate that the capacity expansion model (TEMOA-TO in our project) has built flexible and dispatchable generation assets in a considered jurisdiction.
- If a decentralized generator is connected at low-voltage levels (i.e., distribution grid, <115 kV), its generation is mainly used in the two main ways: self-consumed by a prosumer when generation is available, and the excess is injected back to the utility distribution grid in exchange of some reward (depending under which program generator is connected). Generation from prosumers at a distribution level is not exported to the transmission grid (operator level). However, installed capacity of renewable generation at a distribution level and its operation will reshape the total net load in different transmission areas. One of the examples of such load modification is a duck curve effect first described for California and that may become noticeable in Toronto in case of high deployment of PV capacities (discussed in Section 2.2).

While SILVER-TO gives the possibility to input centralized generation (as well as storage) at a grid operator scale, we observe that in reality there is simply not enough space in Toronto to deploy such high-capacity generators to be directly connected to the transmission grid. All renewable generators in Toronto are

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[40] Kim H. Olave-Rojas D. Álvarez-Miranda E. and S. W. Son (2018). In-depth data on the network structure and hourly activity of the central chilean power grid. *Sci. Data* 5: 1–10.

deployed at various scale of distributed generation (DG), e.g., residential, and commercial buildings deploying rooftop PV panels. The maximum capacity of these generators is not only limited by the resource potential (e.g., solar irradiation), but also by physical constraints, e.g., roof surfaces. This is confirmed by other analysis, such as the estimation of rooftop solar potential done by the Environmental Insights Explorer of Google, which finds the maximum capacity of a standalone PV technology that may be deployed in Toronto to be no more than 50 kW[41]. Under current and future urban design, the possibility of large-scale generation deployment in Toronto tends to be non feasible. But SILVER-TO has a possibility to test this in case of some major urban or technological changes that will allow such deployment.

In the final version of SILVER-TO, Toronto is mainly supplied through power imports from the province at different 230 kV transmission TS, such as Malven, Sheppard, Manby, Horner and Rexdale, and from the Portland Energy Center gas-fired power plant at Hearn SS. Each power import and generator were characterized by a cost factor (related to operation cost of a specific generator type) and used by the model to optimize power generation dispatch. SILVER-TO relies on cost factors defined for Ontario[42]. For imports, the cost factor represents the weighted average of cost factors for different types of provincial generators depending on their total generation over a year. Note that the cost curve value for imports will depend on the provincial strategy regarding power generation mix. Import cost factor for Toronto may be different for the Reference case involving fossil fuel generators and for net zero with larger renewable generation. However, this parameter will not impact Toronto power supply that must be addressed independently of the energy mix in the rest of the province.

Similar to the transmission lines, power generation characteristics do not require modification from the user. However, due to the data limitation regarding power systems in general that led to different assumptions, the user has the possibility to update available power generation and its technical specification if additional information becomes available.

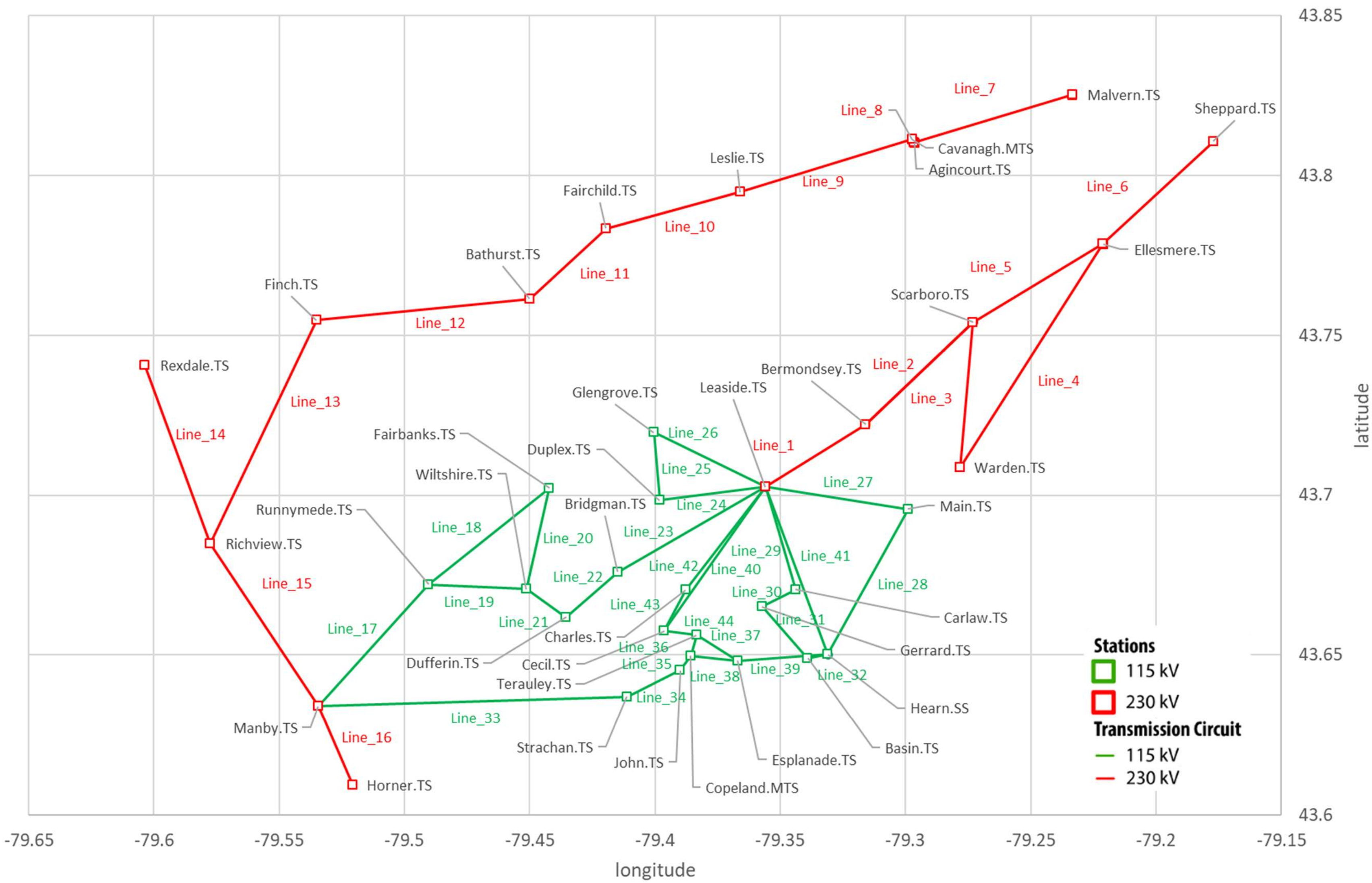
3.2.3. Demand Centres

Demand centres specify the TS to which urban distribution systems are connected. Demand centres must be specifically identified in the input and the user must provide hourly net load associated to the electricity power demand in each transformer zone obtained with the Linking Tool. For model detail about total net load in each transformer zone please refer to Section 2.2.2

[41] Google (2023). Environmental Insights Explorer - Toronto. Online (Accessed in February 2023): https://insights.sustainability.google/places/ChIJpTvG15DL1IkRd8S0KlBVNTI?hl=en-US&solar=a:4332

[42] McPherson M. and B. Karney (2017). A scenario based approach to designing electricity grids with high variable renewable energy penetrations in Ontario, Canada: Development and application of the SILVER model. Energy 138: 185–196.

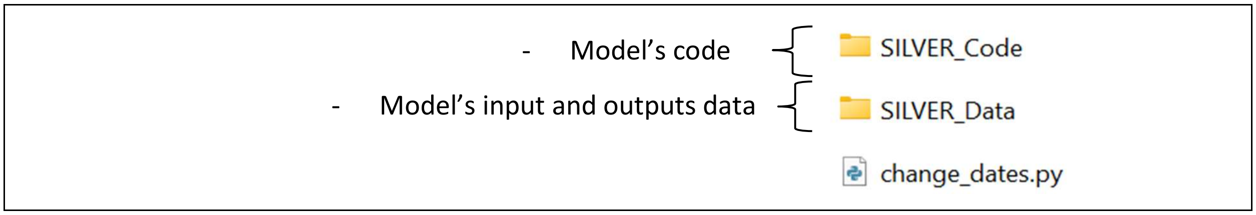
Figure 73. Toronto 115 kV and 230 kV transmission system for SILVER



3.3 How to use SILVER-TO?

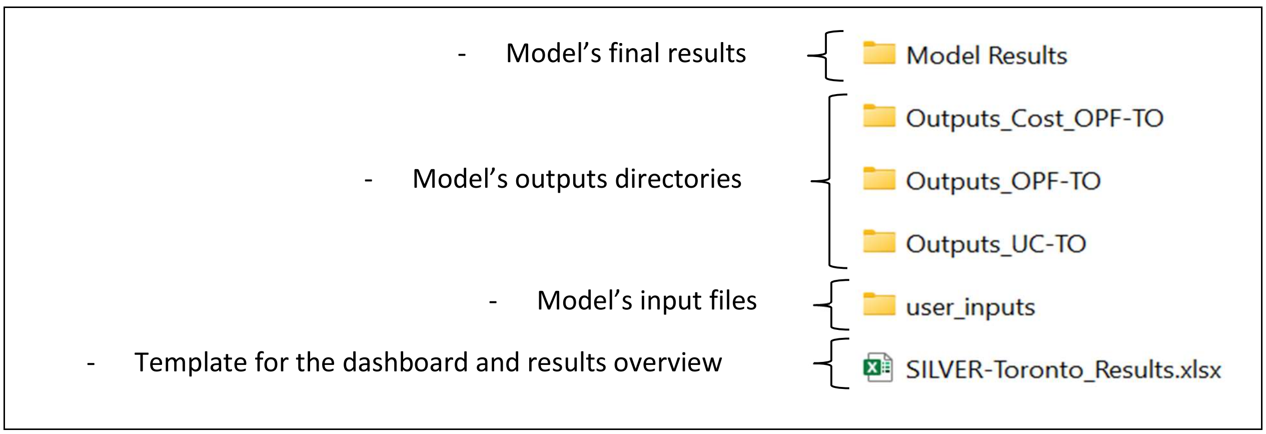
This section presents instructions to run and configure the SILVER-TO model. In SILVER-TO directory, there are various files, including the *silver_env. yaml* used to install SILVER environment, and a user – manual. The *silver* folder is composed of *SILVER_Code* for the model code and *SILVER_Data* for its data (Figure 74).

Figure 74.The SILVER-TO directory



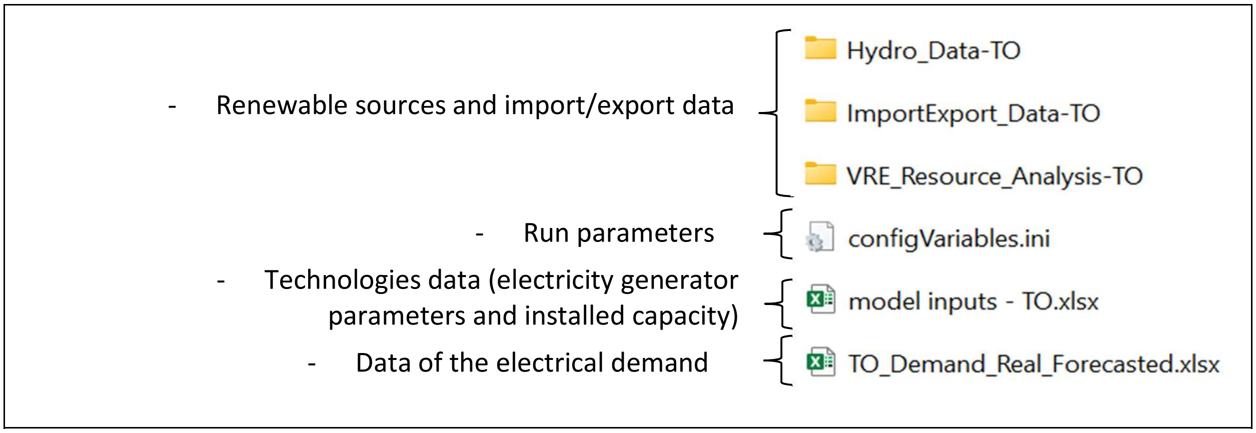
The *SILVER_Data* folder, includes both input and output data. Input data are localised in the *user_inputs* folder while outputs are split in two batches, raw outputs in *Output_xxx* and main results including a Dashboard in *Model Results* (Figure 75).

Figure 75. Structure of SILVER-TO data directory



In the *user_inputs* folder, the two excel spreadsheets describe the power system from power generation to transmission to demand centres (Figure 76). The three folders are used to input specific data on renewable power generation (hydro, solar and wind technologies), and energy trade.

Figure 76. Structure of SILVER-TO input data directory



3.3.1. Install and set SILVER-TO

Download the code folder, unzip it, and place the folder under the C drive.

To run the model, open an Anaconda Prompt and enter the command from Figure 77, followed by enter. Note that the prompt after # are comments and not commands.

Figure 77. Creation of the environment of SILVER-TO

Anaconda Prompt

```
cd [path to ESMIA_SILVER-Toronto directory]

conda env create -f silver_env.yaml #Create the environment

conda env list #Display the list of environments
```

If the environment is correctly installed, a line confirming the installation of silver_env environment, and its location may appear on the anaconda prompt:

Figure 78. Environment installation check

```
(base) C:\Users\esmia>conda env list
# conda environments:
#
base                  *  C:\Users\esmia\anaconda3
linking_tool             C:\Users\esmia\anaconda3\envs\linking_tool
silver_env               C:\Users\esmia\anaconda3\envs\silver_env
temoa-py3                C:\Users\esmia\anaconda3\envs\temoa-py3
```

Open an Anaconda Prompt and enter the commands as per Figure 80 to activate the virtual environment.

Figure 79. Activate SILVER-TO environment

Anaconda Prompt

```
conda activate silver_env #Activate the environment
```

Warning! The *silver_env.yaml* file contains a list of Python modules to be installed for SILVER run. These modules, more specifically, their versions may evolve. This may require updating modules version based on the installation error message.

3.3.2. Configure the scenario

The structure of the *user_inputs* folder is provided above in Figure 76. There are files used to input data and one file to select run parameters.

Data input files

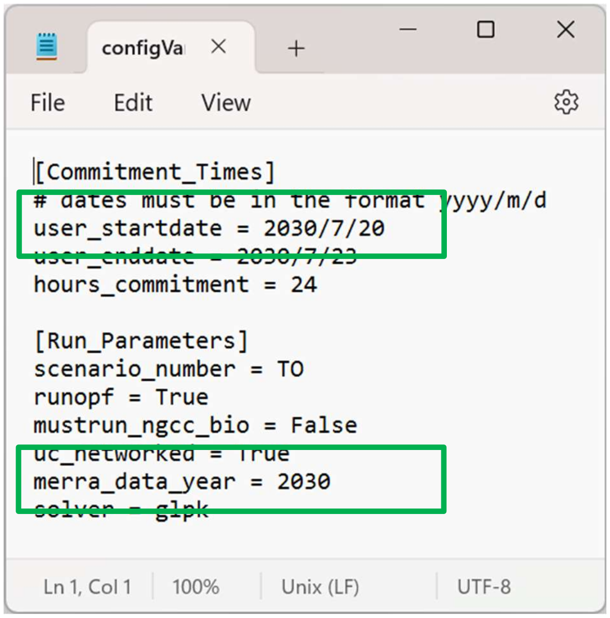
To use the SILVER-TO model, the user only needs to modify the electrical demand in the file *TO_Demand_Real_Forecasted.xlsx*. The other files on renewable technologies, import/export flows and existing technologies for power generation come from SILVER-Ontario but could be refined to Toronto case in the future.

In *TO_Demand_Real_Forecasted.xlsx* file, there are four sheets: two are an input from the user (‘Zonal_Demand_forecasted’ and ‘Zonald_Demand_Real’), and the other two are calculated from those input data. For SILVER-TO, the hourly real and forecasted zonal demands are the same and come from the total net load calculated by the Linking Tool. The total net load matrix calculated for each transformer nodes, is the result to provide to SILVER-TO. To link these results to SILVER-TO, copy the ‘TNL’ sheet from the Linking_Tool_.xlsx, paste those data in the TO_Demand_Real_Forecasted.xslx file, sheets “Zonal_Demand_Real” and “Zonal_Demand_Forecasted”.

Run parameters

The user can access the file *configVar.ini* to modify run parameters (Figure 80). The last line can be modifies to indicate the solver used (e.g., GLPK, CPLEX, Coin CBC). The user can choose the temporal frame of the model. However, the start and end dates as well as the merra_data_year must be the same year as in the input files. To model an other year, it may be chosen in the Linking Tool. The year inputted in *configVar* is indicative, but (not mandatory) it is possible to change this year in all input files of the model, even those that are not use in Toronto case (see Figure 76). Another warning is that the Hours_commitment line 5 must be 24 in order to visualize the results correctly. In the example shown in Figure 80, the user will run SILVER-TO for the days between July 20, 2030, and July 23, 2030 using GLPK solver.

Figure 80. Configuration file for SILVER-TO



3.3.3. Run the model

Open an Anaconda Prompt and enter the following commands to activate the virtual environment and run SILVER-TO (Figure 81).

Figure 81. Run SILVER-TO

Anaconda Prompt

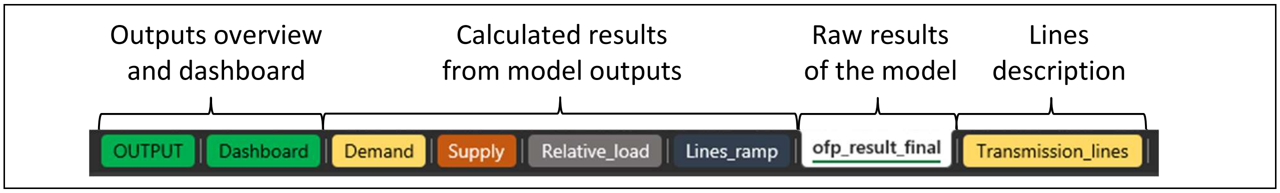
```
conda activate silver_env #Activate the environment
cd [path to silver/SILVER_Code directory]
Python SILVER_VER_18.py #Run the model
```

Outputs are in the folder *silver/SILVER_Data* and they are also automatically added to the file *SILVER-TO_Results.xlsx* for visualization.

3.4 Results overview and interpretation

The results of SILVER-TO are summarized in the excel spreadsheet *SILVER-TO_Results.xlsx* (Figure 82). This spreadsheet calculates, from SILVER-TO outputs, the relative load, the lines ramp, the importation of electricity during the day and the peaking of power generation.

Figure 82. Structure of the excel outputs overview and dashboard



3.4.1. Example of model output

SILVER-TO tests the operational viability of a specific energy transition strategy from the power grid operational perspective for a certain time period (e.g., year, season). The model will provide a result dashboard providing an overview and key statistics for a selected operational time period. Please note that at this point results in this section are provided for illustration purposes and may not entirely reflect a particular scenario analyzed within TEMOA.

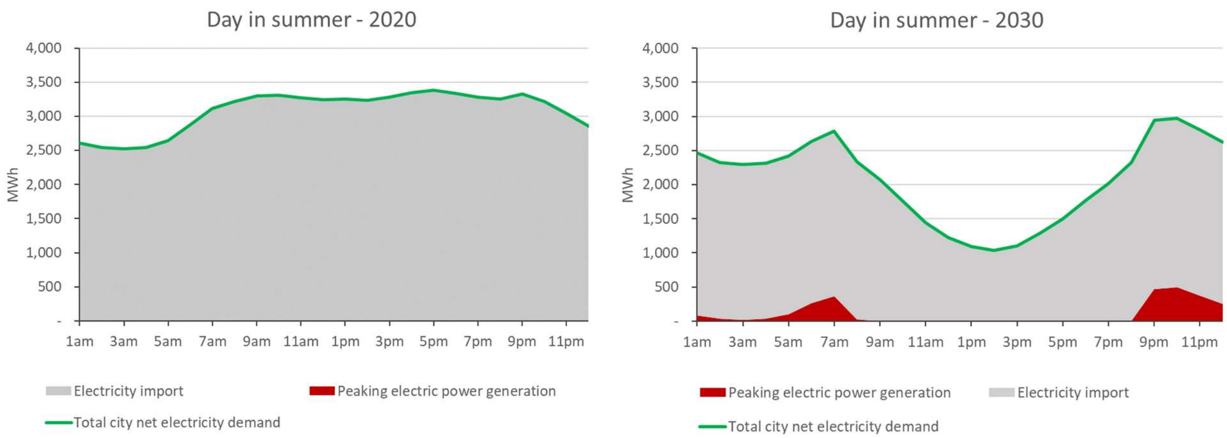
The modification of the city total net load due to the increased penetration of renewable generation, distributed storage and EV may increase load ramps and, as a consequence, increase the need to use peaking power generation. Table 22 provides an example of power system operation statistics that will be available for the user in the “OUTPUT” sheet of SILVER-TO results spreadsheet. In this sheet, the user can select the threshold leading to the increase of heat losses and the hourly ramps threshold. From those values, it calculates the following metrics on the risks for transmissions lines.

Table 22. Example of seasonal statistics

Parameter	Unit	July	
		2020	2030
Toronto electric power demand characteristics			
Total demand	MWh	2,224,116	1,596,727
Maximum peak	MW	4,498	3,734
Maximum ramp-down	MW/h	-301	-1,488
Maximum ramp-up	MW/h	310	1,404
Transmission lines 230 kV			
Number of lines exceeding defined threshold leading to increase losses	Number	7	7
Duration that lines operate with increased losses	h	2,199	1,723
Number of lines with hourly ramp exceeding defined threshold	Number	5	9
Number of events per season	h	200	234
Transmission lines 115 kV			
Number of lines exceeding defined threshold leading to increase losses	Number	6	7
Duration that lines operate with increased losses	h	1,755	422
Number of lines with hourly ramp exceeding defined threshold	Number	5	8
Number of events per season	h	5	86

Figure 83 provides an example illustration of generators power dispatch to supply electricity demand in the city for a day in summer in 2020 and 2030. The following figures are available in the "Dashboard" sheet of the results of SILVER- TO. As it can be noticed, the total net load in 2030 summer day may indeed generate important morning ramp-down and evening ramp-up requiring peaking power generation to address daily peak. This observation is aligned with different analysis pointing out the importance of peaking generation or other measures, such as high-capacity battery energy storage, in the future.

Figure 83. Example of electric supply through transmission lines to address demand in Toronto illustrated for day in summer in 2020 and in 2030 (under increasing penetration of renewable generation)



Changes in the total net load, decreasing electricity power demand during some daily periods and increasing during others, may also change loads on the transmission power lines. Figure 84 and Figure 85 illustrate how transmission lines within the Toronto may be loaded for the same days in winter and summer, but under different levels of renewable power generation, storage, and EV. The modification of the total net loads in different Toronto areas may lead to the two major effects:

- increase of the load level that may require transmission lines to operate at more than 40 per cent of their maximum capacities, increasing resistive heating and generating higher energy losses;
- increase of load variation of transmission lines that may result in additional equipment stress.

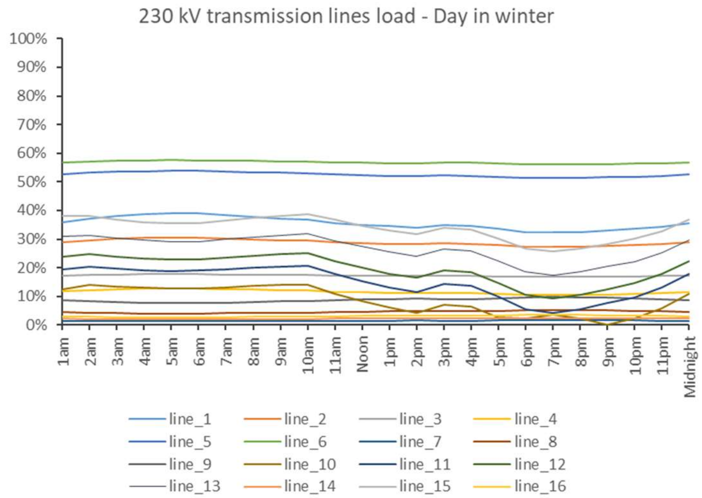
SILVER-TO captures the following potential trends that may arise due to the increase use of distributed renewable generation in the city (comparing results for the same period in 2020 and in 2030 from Figure 84, Figure 85 and Table 22):

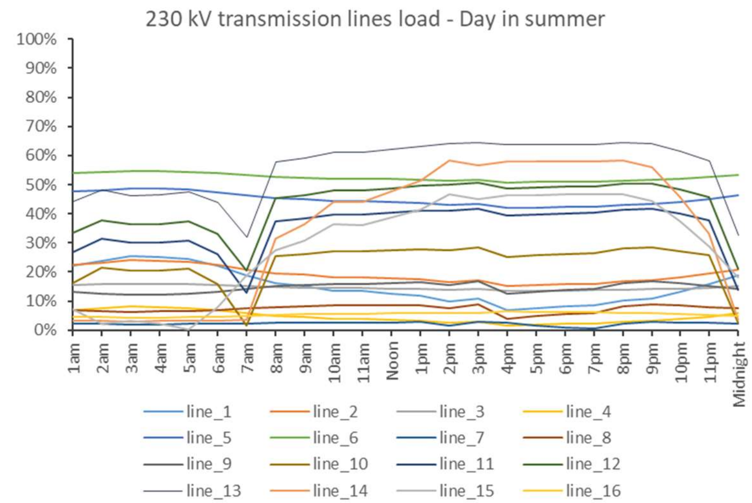
- the total electric power demand and peak may decrease due to the increase in electricity generation with distributed renewable resources;
- power demand peak may decrease as well, especially in summer when it coincides with PV power generation;
- due to variability of renewable generation and adoption of specific behaviours for batteries and EV charging, load ramp-down and ramp-up may considerably increase;
- in the future, more transmission lines may experience important ramps and the event duration will more likely become longer;
- while the results in this section indicate that lines overcharge may be less important in the future, this may change depending on the adopted scenario.

The guidance on results interpretation and actions for risk mitigation is presented in Section 3.4.2.

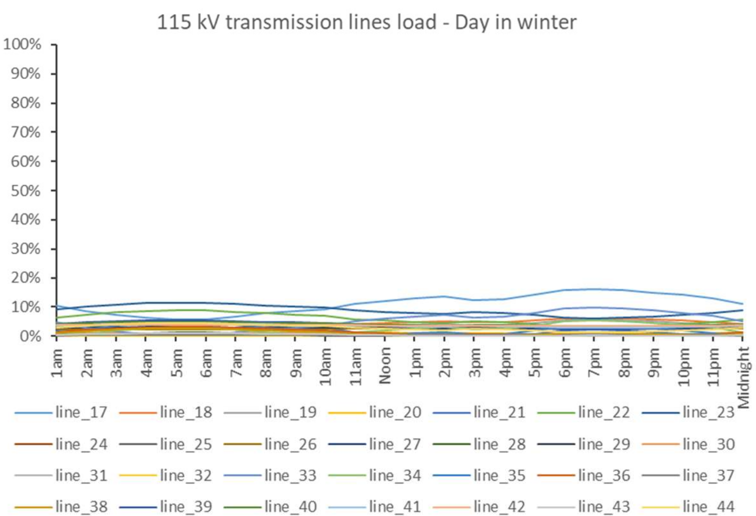
Figure 84. Example of transmission lines relative load 2020

Day in winter and summer – 230 kV transmission lines





Day in winter and summer – 115 kV transmission lines



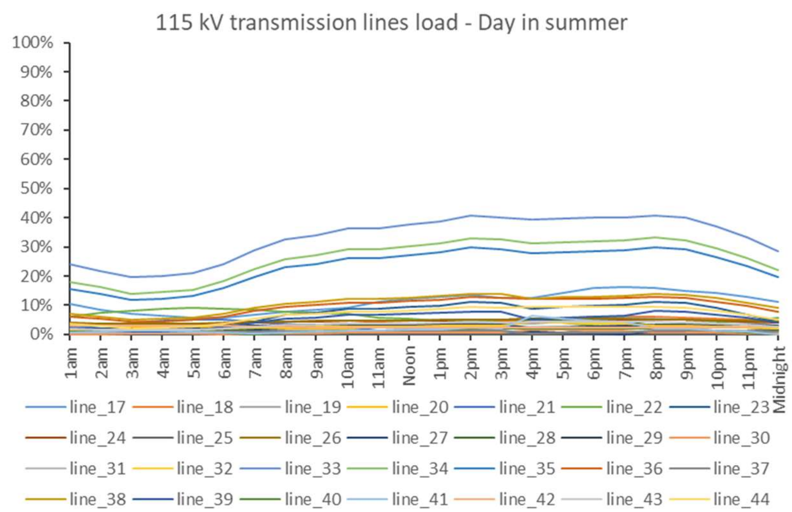
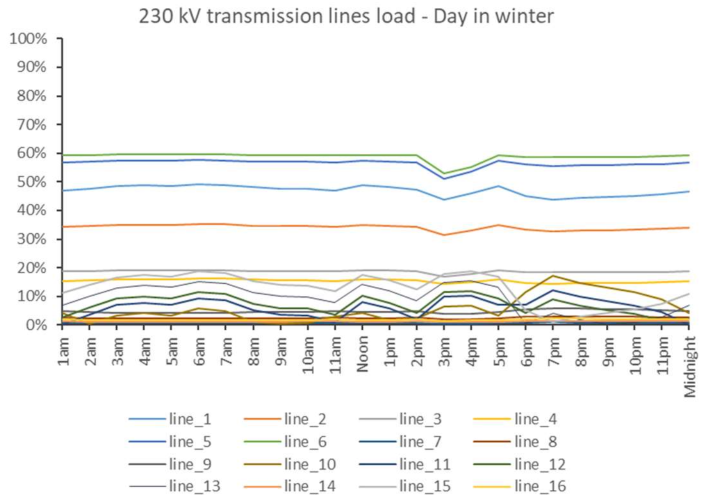
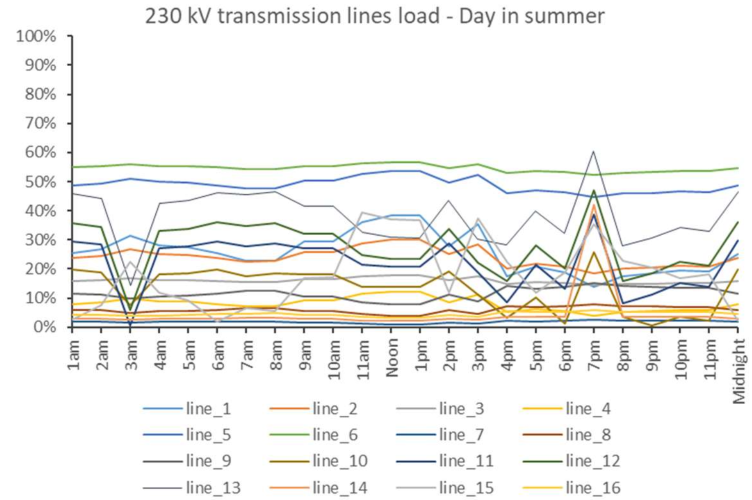


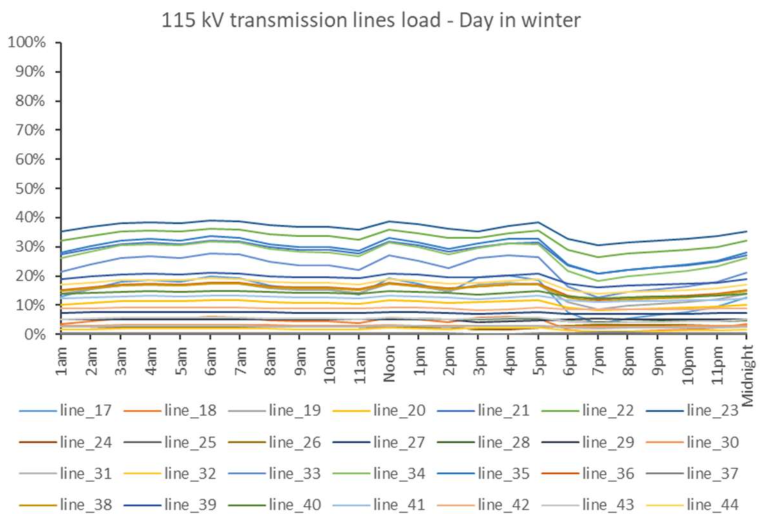
Figure 85. Example of transmission lines relative load in 2030

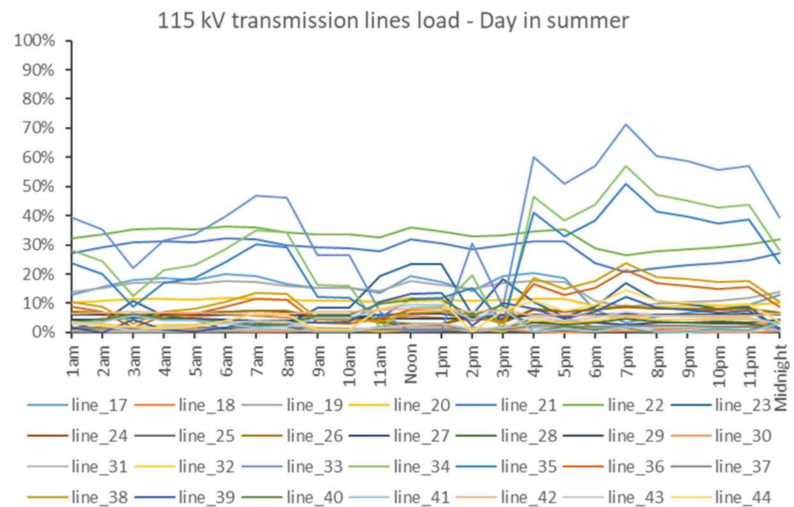
Day in winter and summer – 230 kV transmission lines





Day in winter and summer – 115 kV transmission lines





3.4.2. Identification of risks and mitigation actions

An increase in power load at different nodes of a power grid may affect its stability against overloads of transmission lines. Line overload may also happen with the increasing distributed generation capacity (especially PV) operated in a self-consumption mode. The difference in electric power demand and the amount of available solar energy throughout the day reshapes the total net load in different transmission regions starting to follow the so-called "duck curve". This effect changes power grid operational conditions creating[43]:

- short, steep ramps that require bring on or shut down generation resources to meet an increasing or decreasing electricity demand quickly, over a short period of time;
- overgeneration risk – when more electricity is supplied than is needed to satisfy real-time electricity requirements;
- decreased frequency response – when less resources are operating and available to automatically adjust electricity production to maintain grid reliability.

SILVER-TO captures the potential risk of transmission lines overloading in Toronto as a result of massive deployment of renewable generation, storage, and EV at the distribution side. Table 23 provides guidance on how SILVER-TO modelling results could be interpreted and what policies may be adopted at the municipal government level to mitigate different risks. For better understanding on which policies may be more suitable for adjustment it is recommended to consider SILVER-TO results together with the Linking Tool result dashboard.

Although, Toronto contributed to the Ontario power peak demand with 18 per cent in 2020[44], its peak contribution may significantly grow with the increase in electrification by 2050. Therefore, the energy strategy adopted at the city level may have an influence on the provincial power system which generates some risks. Table 23 provides the examples of such risks, as well as what may be done at the city level. This highlights the need for better coordination between City and provincial policies.

[43] CAISO - California Independent System Operator (2015). What the duck curve tells us about managing a green grid.

[44] OEB – Ontario Energy Board (2020). Yearbook of Electricity Distributors 2020/2021.

Table 23. SILVER-TO results interpretation guidance

#	Observation	Associated risks	Policy actions (city level)		Insights for other actors involved in energy transition (province, system operator, etc.)
			Examples of policy to mitigate potential risks	Decision-support actions (with modelling tools)	
1	Increase of the city net load ramps	Toronto transmission system: Equipment stress, wear and tear, failure	Demand response program, such as Hilo smart home of Hydro-Quebec, giving the possibility to reduce energy use during peak periods in exchange of a cash reward[45]	Demand Response potential (per cent of load decrease) may be tested directly with SILVER-TO. Incentives (reward program) for consumers that may lead to such demand decrease must be explored with specific demand response tools.	Communication on potential changes in load profile may help to: - define optimal power generation mix (baseload, intermediate, peak plants) - implement technologies (such as large-scale storage) for better management of variable load - plan various system upgrades.
			Increase residential storage capacity for peak demand shaving and ramp rate decrease[46]	Suitable incentive to increase storage capacity may be tested via TEMOA, and the Linking Tool will generate new total net load profiles by considering the increasing storage capacity. SILVER-TO will advise on the policy effect from the operational perspectives.	
			Implement policies to promote EV coordinated charging when charging hours are scheduled to reduce the impact on the load while respecting charging demand[47]	User may adjust EV charging policy in the Linking Tool that will build new total net load profiles. Incentives (reward program) for consumers that may lead to such demand decrease must be explored with specific demand response tools.	
2	Lines prolonged overload	Toronto transmission system: Increasing equipment	Test same policies as in #1	Test same actions as in #1	Communication on potential lines overload depending on urban policies may help to:

[45] Hydro-Quebec (2023). Hilo smart home. Online (Accessed in February 2023): https://www.hydroquebec.com/residential/energy-wise/saving-during-peak-periods/hilo-smart-home-service.html.
[46] CAISO - California Independent System Operator (2019). Energy Storage: Perspectives from California and Europe.
[47] Alvarez Guerrero J. D. Acker T. L. and R. Castro (n.d.). Power System Impacts of Electric Vehicle Charging.

		temperature, stress, wear and tear, failure			- plan strategy on transmission lines upgrade or other projects - plan various system upgrades.
3	Increase in the city average load and peak – Increase Toronto contribution to the provincial load and peak[48] (may be combined with #1 and #2)	Power generation at provincial level: Impossibility to meet the increasing city demand and/or to address peak with the existent power generation mix. Power transmission from generators to consumers (Toronto City) – Risk of provincial lines overload leading to equipment stress, wear, and tear, and, eventually, increased risk of failure. Toronto City – Risk of demand not met	Promote energy efficiency measures to decrease average load of city/transmission region	Reinforce energy efficiency policies (e.g., buildings and technologies) to be tested via TEMOA, the Linking Tool will build new total net load profiles by considering new energy demand under improved efficiency, SILVER-TO will advise on the policy effect from the operation perspectives.	Communication on potential increase in average city load and peak contribution may help to: - define optimal power generation mix (baseload, intermediate, peak plants) - implement technologies (such as large-scale storage) for better management of variable load plan strategy on transmission lines upgrade or other projects.
			Promote policies leading to the increase of distributed generation adoption at consumer level, increase of district CHP capacities.	The increase of distributed generation capacities may be tested via TEMOA. The Linking Tool will build new total net load profiles by considering the increasing storage capacity, SILVER-TO will advise on the policy effect from the operation perspectives.	
			Test same policies as in #1	Test same actions as in #1	

[48] Subject to assumptions regarding Ontario energy strategy including how provincial power demand and summer/winter peaks may evolve in the future.

ANNEX A. Net Zero Strategy and corresponding modelling assumptions in TEMOA

Table 24. Policy modelling for the building sector

Policy ID	Name	Description	Modelling
BAP-BDG-1	Toronto Green Standard (TGS) Tier 4 for new residential buildings by 2032	TGS Tier 4 for new residential buildings by 2031	o Ban standard efficiency equipment by 2030 o 100 per cent of parking are equipped with 240V electric charger o TEUI and TEDI rate applied to new building by 2030
BAP-BDG-2	BAP residential retrofits	Retrofit 6,000 units per year. Annual electricity percent savings per building - 10 per cent Annual thermal demand percent savings per building - 35 per cent	o Ban standard efficiency equipment by 2030 o Invest in energy conservation measures by 35 per cent for 15 per cent of residential building by 2050
BAP-BDG-3	TGS Tier 4 for new commercial buildings by 2032	TGS Tier 4 for new commercial buildings by 2031	o 100 per cent of parking are equipped with 240V electric charger o TEUI and TEDI rate applied to new building by 2030
BAP-BDG-4	BAP commercial building retrofits	Retrofit 4,500 buildings by 2050	o Ban standard efficiency equipment by 2030 o Invest in energy conservation measures by 35 per cent for 19 per cent of commercial building by 2050
BAP-BDG-5	TGS Tier 4 for new public buildings by 2032	TGS Tier 4 for new public buildings by 2031	o 100 per cent of parking are equipped with 240V electric charger o TEUI and TEDI rate applied to new building by 2030
BAP-BDG-6	BAP public building retrofits	Retrofit All buildings by 2050	o Ban standard efficiency equipment by 2030 o Invest in energy conservation measures by 35 per cent for 100 per cent of public building by 2050
NZ50-BDG-1	Decrease size of new dwellings	30 per cent increase in floorspace intensity from 2016 by 2040 (for all new dwellings)	o Decrease new residential building size gradually by 30 per cent from 2023 to 2040
NZ50-BDG-2	High performance new residential buildings	100 per cent Tier 2 by 2021 100 per cent Tier 3 by 2022 100 per cent tier 4 by 2027	o Ban standard efficiency equipment by 2023 o 100 per cent of parking are equipped with 240V electric charger o TEUI and TEDI rate applied to new building by 2023
NZ50-BDG-3	Retrofit residential buildings by 2050	Retrofit 100 per cent of existing buildings by 2050 Savings of 15 per cent electricity, and 75 per cent thermal energy consumption	o Ban standard efficiency equipment by 2023 o Invest in energy conservation measures by 75 per cent for 100 per cent of residential building by 2050
NZ50-BDG-4	Residential heat pumps by 2050	Convert 100 per cent of residential water and space heating to heat pumps by 2050	o Constrain technology share for water and space heating in 2050

Policy ID	Name	Description	Modelling
NZ50-BDG-5	New industrial buildings improved performance	Industrial newbuilt energy intensity reduction (45 per cent from base year) reached by 2031 and applies to lighting, space heating and water heating end uses	o No vintage disaggregation for industry. o Invest in retrofit measure for industry to reach 50 per cent of efficiency gain by 2050
NZ50-BDG-6	Industrial building retrofits	Retrofit all industrial buildings by 2050 to achieve 50 per cent reduction of industrial energy use intensities for lighting and space and water heating end uses	
NZ50-BDG-7	Industrial process improvements	Reduce natural gas consumption by 30 per cent by 2030 and 60 per cent by 2050 Convert 100 per cent of remaining natural gas for process heat to hydrogen by 2050 Capture 90 per cent of waste heat from industry	o Reduce natural gas share in industrial building energy consumption by 30 per cent in 2030 and 2060 in 2050 o Invest in Waste Heat recovery for industry
NZ50-BDG-8	Decreased office space per employee	Reduced office floorspace per employee by a 'mobility factor' of 1.7 (i.e., 20 people per 12 desks), then allocate new commercial floorspace along lines of employment projection. Results in reduced growth in commercial/office floorspace (for new office)	o Decrease office growth projection
NZ50-BDG-9	High performance new public buildings	100 per cent Tier 2 by 2021 100 per cent Tier 3 by 2022 100 per cent tier 4 by 2027	o 100 per cent of parking are equipped with 240V electric charger o TEUI and TEDI rate applied to new building by 2023
NZ50-BDG-10	High performance new commercial buildings	100 per cent Tier 2 by 2021 100 per cent Tier 3 by 2022 100 per cent tier 4 by 2027	o 100 per cent of parking are equipped with 240V electric charger o TEUI and TEDI rate applied to new building by 2023
NZ50-BDG-11	Retrofit public buildings by 2050	Retrofit 100 per cent of existing buildings by 2050 Savings of 15 per cent electricity, and 75 per cent thermal energy consumption	o Ban standard efficiency equipment by 2030 o Invest in energy conservation measures by 75 per cent for 100 per cent of public building by 2050
NZ50-BDG-12	Retrofit commercial buildings by 2050	Retrofit 100 per cent of existing buildings by 2050 Savings of 15 per cent electricity, and 75 per cent thermal energy consumption	o Ban standard efficiency equipment by 2030 o Invest in energy conservation measures by 75 per cent for 100 per cent of commercial building by 2050
NZ50-BDG-13	Non-residential heat pumps by 2050	100 per cent electric heat pumps for space and water heating in non-residential buildings by 2050	o Constrain technology share for water and space heating in 2050

Policy ID	Name	Description	Modelling
NZ50-BDG-14	Green hydrogen in buildings	10 per cent hydrogen blended into natural gas in residential and commercial buildings by 2050	o Constrain energy share for natural gas and hydrogen by 2050
NZ50-BDG-15	Electrify residential appliances by 2050	Phase out residential natural gas appliances by 2050	o Constrain technology share for natural gas appliances by 2050
NZ40-BDG-1	Residential heat pumps by 2040	Convert 100 per cent of residential water and space heating to heat pumps by 2040	o Constrain activity target for non-HEP water and space heating in 2040
NZ40-BDG-2	Electrify residential appliances by 2040	Phase out residential natural gas appliances by 2040	o Constrain energy share for natural gas and hydrogen by 2040
NZ40-BDG-3	Hydrogen for process heating by 2040	Use hydrogen for 100 per cent of process heating by 2040	o Constrain energy share for industrial process by 2040
NZ40-BDG-4	Non-residential heat pumps by 2040	Convert 100 per cent of non-residential heating to heat pumps by 2040	o Constrain activity target for non-HEP water and space heating in 2040

Table 25. Policy modelling for transportation sector

Policy ID	Name	Description	Modelling
BAP-TRA-1	Electrify transit by 2050	50 per cent of fleet electric by 2030; 100 per cent by 2050 100 per cent electrification of GO by 2025	o Technology share for transit fleet by 2025 (or 2030)
BAP-TRA-2	Active and transit infrastructure/service	Active and transit mode shares improved through as-planned infrastructure improvements	o Demand shift from road to transit
BAP-TRA-3	City fleet 45 per cent electric by 2030	Transition 45 per cent of City-owned fleet to low-carbon vehicles by 2030; 65 per cent GHG reduction by 2030 (from 1990 levels)	o Technology share for public fleet by 2030
BAP-TRA-4	Electrify personal vehicles by 2050	Electrify 98 per cent of personal vehicles by 2050 (achieved from 100 per cent EV sales in 2040)	o Technology share for passenger transportation road car and light trucks
BAP-TRA-5	BAP commercial vehicle electrification	Light duty commercial - 50 per cent new sales EV by 2040 Long-haul - background 2.5 per cent electrification rate	o Market share 50 per cent Light truck sales o Technology share on long-haul electrification
NZ50-TRA-1	Increased bus lanes and service frequency	Convert one lane of traffic to exclusive bus lanes on all arterials Increase service frequency on all transit routes: bus by 70 per cent, streetcar by 50 per cent,	o Demand shift from road to transit by 2050

Policy ID	Name	Description	Modelling
		subway off-peak service increased to every 3 mins	
NZ50-TRA-2	Road tolls	Tolls of $0.66/km on all arterial roads	o Demand shift from road to transit by 2050
NZ50-TRA-3	Free transit	No transit fares	o Demand shift from road to transit by 2050
NZ50-TRA-4	Work from home	50 per cent of professional/management/technical and general office/clerical workers in the GTHA work from home on any given day	o Demand shift for home to work transportation
NZ50-TRA-5	Switch remaining personal internal combustion engine (ICE) vehicles to electric	Switch all remaining ICE vehicles 11 years or older to electric from 2040 onwards	o Technology share for ICE vehicles by 2040
NZ50-TRA-6	Electrify transit by 2040	Electrify 100 per cent of transit by 2040	o Technology share for transit fleet by 2040
NZ50-TRA-7	E-bikes	Shift 75 per cent of car and transit trips under 5km to ebikes by 2040	o Demand shift for cars, light trucks, and transit to ebikes by 2040
NZ50-TRA-8	Increase walking and cycling	Shift 75 per cent of trips under 2km to walking by 2040	o Demand shift for car and transit to walk by 2040
NZ50-TRA-9	Electrify City fleet by 2050	Electrify 100 per cent of City fleet by 2050	o Technology share for electric vehicles by 2050
NZ50-TRA-10	Biofuels City fleet	In 2025, begin purchasing renewable diesel for diesel vehicles and equipment (30 per cent renewable diesel for City fleet)	o Energy share for diesel City fleet (30 per cent Renewable diesel by 2025)
NZ50-TRA-11	Electrify commercial vehicles by 2050	Electrify 100 per cent of commercial vehicles by 2050	o Technology share for commercial electric vehicles by 2050
NZ50-TRA-12	Biofuel aviation	Aviation runs on 100 per cent low emissions fuels by 2050	o Energy share for passenger air transportation only o Freight air transportation is excluded from this policy
NZ50-TRA-13	Biofuel rail	Rail runs on 100 per cent biofuel by 2050	o Ban all rail technology other than hydrogen and renewable diesel
NZ40-TRA-1	Electrify personal vehicles by 2040	Electrify 100 per cent of personal vehicles by 2040	o Technology share for personal electric vehicles by 2040
NZ40-TRA-2	Electrify commercial vehicles by 2040	Electrify 100 per cent of commercial vehicles by 2040	o Technology share for commercial electric vehicles by 2040

Table 26. Policy modelling for energy sector

Policy ID	Name	Description	Modelling
BAP-ENE-1	Install contracted district energy systems	2016 DE + Contracted DE systems	o Capacity constraint for district heating and district cooling capacity
BAP-ENE-2	BAP realistic transition	Enable the optimization of a growing share of energy imports (+5 per cent / year)	o Energy share by sector decrease by 5 per cent per year
NZ50-ENE-1	Renewable and expanded district energy	All DE systems are 100 per cent renewable by 2030- natural gas and electric cooling are replaced by Renewable natural gas (RNG) and cold water. All of the City's currently planned DE expansions are installed	o Demand shift for fuel share in district heating technology o Technology share constraint for district cooling energy production
NZ50-ENE-2	Renewable energy plus storage	Wind capacity scaled up to 200 MW by 2050 Onsite battery storage scaled up to 2000 MW by 2050 Ground mount PV on 50 per cent of parking lots 100 per cent of buildings have solar PV installed by 2050, where feasible	o Min capacity by 2050 for wind 200 MW, solar 3675 MW (half of maximum rooftop solar potential) and battery storage 2000 MW
NZ50-ENE-3	NZ50 realistic transition	Enable the optimization of a growing share of energy imports (+5 per cent / year)	o Energy share by sector decrease by 5 per cent per year
NZ40-ENE-1	NZ40 realistic transition	Limit fuel change in by sector import energy share by 5 per cent per year	o Energy share by sector decrease by 5 per cent per year

Table 27. Policy modelling for waste sector

Policy ID	Name	Description	Modelling
BAP-WAS-1	Waste diversion BAP	Increase waste diversion rate to 70 per cent by 2025	o Shift demand from landfill to green Bin and recycling in 2025
BAP-WAS-2	Increase efficiency of water pumps	Increase efficiency of water distribution pumps	o Increase efficiency of water distribution pumps (this is not treated as new technology; this policy will impact both historical and future years)
BAP-WAS-3	RNG from landfill	Greenlane; Keele Valley; All wastewater plants include biodigesters by 2050	o As it is a low-cost measure, the model will invest to full potential by itself. No additional constraint is required
NZ50-WAS-1	Waste diversion Zero by 2050	Increase waste diversion rates beyond the 70 per cent by 2026 target, to 95 per cent by 2050	o Shift demand from landfill to Green Bin and recycling gradually from 2026 to 2050
NZ40-WAS-1	Ban landfill organics	Zero organics in landfills by 2025	o Shift demand from landfill to Green Bin in 2025

ANNEX B. Approach to model PV shading

To find hourly shading factors, the rooftops had to initially filtered by both slope and aspect (orientation). Both slope and aspect rasters were created from the DSM raster using built-in QGIS functions of Slope and Aspect. From this, suitable rooftop areas were initially filtered based on the following criteria:

- Raster files overlapping with building vectors;
- South facing and/or flat (orientation[49] between 90° and -90° and/or slope less than 5°); and
- Not a vertical or near vertical wall (slope less than 70°).

Shading rasters for each hour the sun was out, were created for the entire city using the DSM raster, the solar azimuth and elevation, and the Hillshade function, with the z-factor (exaggeration factor) set to 1 to mimic real shading conditions. These hourly rasters were then clipped to only the suitable rooftop areas found. Using the Zonal statistics function, the average hourly shading function on each suitable rooftop area, as well as the size of the horizontal projection (footprint) of the suitable rooftop area, was found for each building footprint. Finally, the actual size of the suitable rooftop area was calculated based on the size of the horizontal projection of the suitable rooftop area and the associated slope.

Within this process, two key assumptions were made due to data availability and computational processing capabilities, respectively. Firstly, within the DSM raster, the surface coverage that was trees and/or vegetation was not considered separate from building coverage, as the majority would be naturally filtered out through suitable rooftop analysis. Since the orientation of the tree and/or vegetation would not be entirely south facing, it was assumed that the majority would've been filtered out through that alone. Further, the south facing portions of trees and/or vegetation would be such a small, discontinuous amount of rooftop area, it was assumed that it would be filtered out further on in the analysis. Secondly, the shading factor was not analyzed for every hour of the year, only solstices and equinoxes were. Based on the historical trends in azimuth and elevation changes, as well as sunset and sunrise times, the rest of the year was linearly interpolated from the solstice and equinox shading data. Shading data are first calculated by forward sortation area codes (CDFSA) and then by transformer zones (see matrix in "Solar_Shading_avg" sheet in *Input.xlsx* file).

[49] Based on traditional compass orientation of north at ±360°

ANNEX C. Mandatory software installation

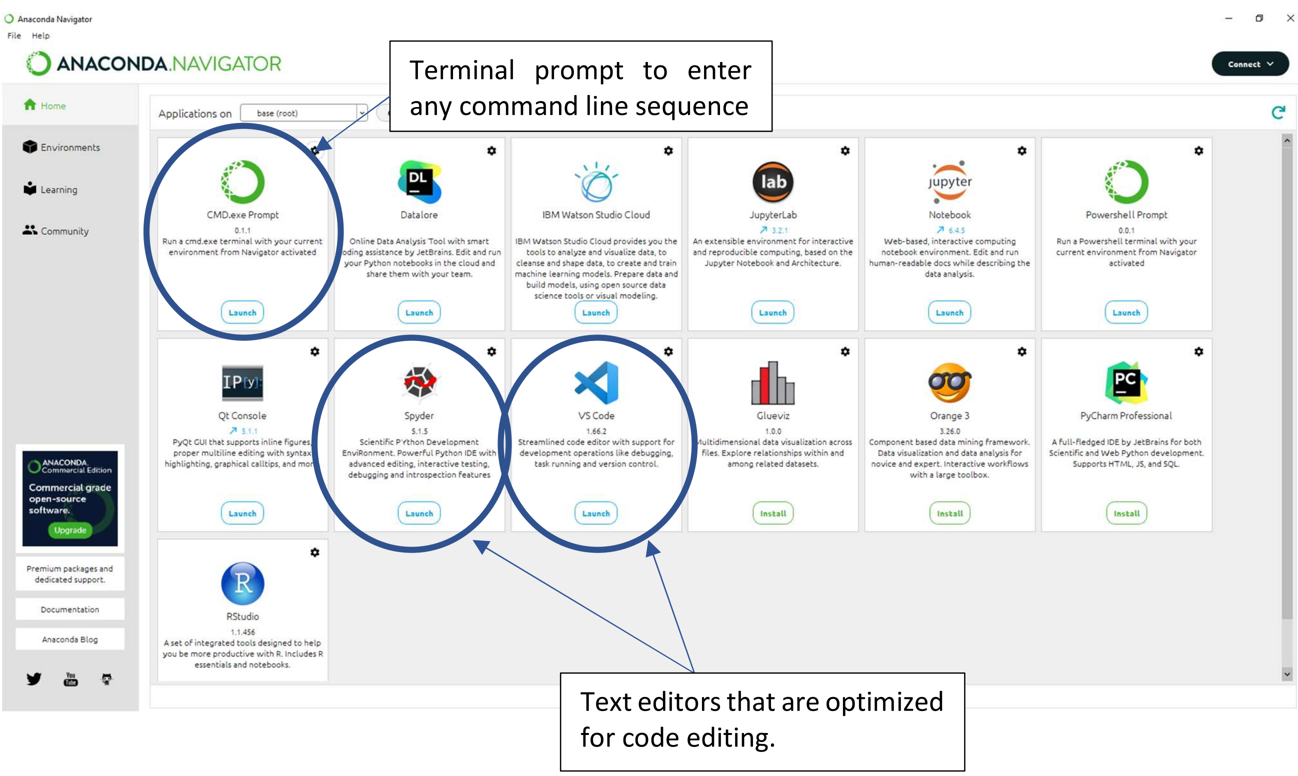
General warning:

To avoid basic errors, do **not use any space or special characters in any folder or file** name you are using for your model. Moreover, models need to be run locally and not on a drive.

Install Anaconda

Download the Anaconda software: https://www.anaconda.com/
Follow the installation setup with all default parameters.

Anaconda Navigator is the navigator that allows to access all the tools installed with the Anaconda software.



Check if Python is installed correctly

Open the Command Prompt (CMD) type the following command, followed by enter:

Command Prompt

```
Python --version
```

If Python is correctly installed a line confirming its installation and version should appear on the command prompt:

```
(base) C:\Users\esmia>python --version
Python 3.9.7
```

If Python is already installed on your machine, please check the Python version, the minimum requirement is Python 3.

If Python is not installed, download it from here: https://www.Python.org/downloads/

Install Solvers

Install CPLEX (commercial solver with a free academic license):

https://www.ibm.com/academic/technology/data-science

Scroll down and go to the Software tab
Click Download under ILOG CPLEX Optimization Studio (a commercial or academic email is required to register)
Scroll down and check the box for IBM ILOG CPLEX Optimization Studio 20.10 for Windows x86-64 (CC8ASML)
Scroll further down and click I agree then Download Now.
Install the additional IBM Download Director; in this case additional instructions will be given.
Once the Download Director is open, click Launch.
Keep the default settings the same and proceed through the pages.
Enter the following commands into the Anaconda prompt (Run as administrator), followed by enter[50].

Anaconda Prompt

```
Python “C:\Program Files\IBM\ILOG\CPLEX_Studio201\Python\setup.py” build
Python “C:\Program Files\IBM\ILOG\CPLEX_Studio201\Python\setup.py” install
```

Open the “Edit the system environment variables” window (from the Windows search bar).
Open “Environment Variables…” window under “Advanced” tab.
Select the “Path” variable under “System variables” and click “Edit…”

[50] When entering the prompt below, the path on your machine may not be the same as the one specified in this document depending on the version of CPLEX you have installed.

Select "New" then add the following address:

C:\Program Files\IBM\ILOG\CPLEX_Studio201\cplex\bin\x64_win64

Correct CPLEX error after creating TEMOA's environment:

Go to the following folder:

C:\Users\'*name of user*'\anaconda3\envs\temoa-py3\Lib\site-packages\pyomo\solvers\plugins\solvers

Open: *CPLEX.py* with Visual Studio Code (advised) or a text editor:

Copy the following 2 lines:

```
elif tokens[0] == "objectiveValues":
    pass
```

After (Line 617):

```
    tINPUT.close()
```

Before (Line 618):

```
elif tokens[0].startswith("objectiveValue"):
    objective_value = (tokens[0].split('=')[1].strip()).lstrip("\"").rstrip("\"")
    soln.objective['__default_objective__']['Value'] = float(objective_value)
```

Install GLPK solver (free)

Download the latest version here: https://sourceforge.net/projects/winglpk/
Extract the zip folder in the C: drive.
Open the *C:\glpk `version`\w64* copy the address of the folder.
Search in the windows bar "Edit the system environment variables".
Open "Environment Variables..." window under "Advanced" tab.
Select "Path" variable under "System variables" and click "Edit..."
Select "New" then paste the folder address previously copied.
Select "OK"
Open the command prompt and type the following command and the enter:

Command Prompt

```
glpsol --version
```

If GLPK is correctly installed, a line confirming its installation and version should appear on the command prompt:

```
C:\Users\esmia>glpsol --version
GLPSOL: GLPK LP/MIP Solver, v4.65
Copyright (C) 2000-2017 Andrew Makhorin, Department for Applied
Informatics, Moscow Aviation Institute, Moscow, Russia. All rights
reserved. E-mail: <mao@gnu.org>.

This program has ABSOLUTELY NO WARRANTY.

This program is free software; you may re-distribute it under the terms
of the GNU General Public License version 3 or later.
```

Install COIN-CBC solver (free)

COIN-CBC solver is Open-source and offers reasonable performances. For Windows users, the installation guide is described in: https://www.youtube.com/watch?v=QpfIkVDKxY8