Integrated Policy Analysis and Modelling for the Air Pollution Challenge in Chiang Rai (Thailand) and Vientiane (Lao PDR)

Final Project Report

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1. Overview of Project Milestones and Deliverables

1.1 Introduction

Ambient air pollution is a complex challenge affecting health and wellbeing in South-East Asia. In the region, many sources contribute to air pollution including urban and industrial sources, forest fires, vehicle emissions, and agricultural burning. These source activities are linked to a range of drivers which exacerbate the air pollution challenges in the region, including economic, social, and environmental factors which create a complex situation that is difficult to manage effectively. A systemic understanding of these drivers, sources and impacts can help decision makers to develop more effective responses. This can be informed by decision support tools such as systems modelling and scenario analysis.

In this context, UNDP Bangkok Regional Hub commissioned a pilot study for Vientiane province in Laos PDR and Chiang Rai province in Thailand to develop integrated tools for policy analysis and modelling of the air pollution challenge. Through a participatory process including stakeholder workshops, the Millennium Institute has developed an Integrated Ambient Air Pollution (IAP) model for the analysis of policy interventions to address air pollution in these provinces. The model has been developed to better understand the key sources and drivers of air pollution, their implications for health and socio-economic development, and potential policies and interventions to address this challenge. The model has a provincial scale for Chiang Rai province and Vientiane prefecture province and includes an online user interface for each province (Chiang Rai, Vientiane) which can be used to run scenario simulations and explore the effects of different policy options.

The model development process included systems mapping workshops with government, business, civil society and international organizations in both provinces. This helped to identify the key sources, drivers and impacts of air pollution as well as potential policy interventions. The model database was compiled from government data and other available sources and model parameterization was informed by expert literature and stakeholder consultation. A description of the IAP model is available in the model documentation prepared for each province which describes the key components and dynamics, model boundaries and dimensions, key drivers and source activities for air pollutants, the different policies and assumptions, and key data sources. The full datasets used in each model are also available with the model documentation.

The project was undertaken over a period of 26 months, commencing in January 2021 and ending in March 2023. This final project report is the last project deliverable and provides a summary of the main activities and project deliverables as well as important findings, recommendations, outcomes, and lessons learned from the project.

1.2 Reporting on Project Work Plan and Milestones

The experimental pilot project aimed to support policy and decision making to manage the transboundary air pollution challenge in Thailand and Lao PDR. Key project stages included participatory systems mapping and co-design, data collection and technical model development, and policy scenario simulations and stakeholder engagement and training. This section provides a brief summary of the main activities and milestones that were completed over the course of the project with completion dates indicated in **Table 1**.

Table. Project Work Plan and Completion of Milestones

Project Milestone	Key Deliverables	Completion Date
1. Project inception and model conceptualization	Inception workshops held in Chiang Rai (September 2021) and Vientiane (March 2022). Model inception reports for each province including Causal Loop Diagrams for key sources and drivers and potential policy interventions.	July 2022
2. Model design and implementation	Data collection, desk analysis of literature and policy documents and first model iteration for Chiang Rai (August 2022) and Vientiane (January 2023).	January 2023
3. Model review and validation	Review and refinement of models and development of the model user interface for Chiang Rai (December 2022) and Vientiane (February 2023)	February 2023
4. Business-as-usual and scenario analysis	Scenario analysis and training workshops held for Chiang Rai (February 2023) and Vientiane (March 2023) including video tutorials for each model and scenario analysis workshop reports and reporting templates	March 2023
5. Model refinement and final report	Final refinements to the model user interfaces for Chiang Rai and Vientiane. Final model deliverables including: 1. Final model and documentation – for Chiang Rai and Vientiane 2. User manual for Chiang Rai and Vientiane (and video tutorials) 3. Final Project report and recommendations	March 2023

1.2.1 Project inception and model conceptualization

The initial model conceptualization was undertaken through participatory processes in the form of inception workshops for Chiang Rai (September 2021) and Vientiane (March 2022). During the workshops, the participants undertook interactive systems mapping activities using a collaborative online tool (Miro) to identify and link key types, sources and drivers of air pollution as well as their direct and indirect impacts on health, economy and the environment. Participants also identified potential interventions and policies that could reduce air pollution and/or address negative impacts. For each province, participants were divided into groups based on their sector (government, civil society, international organizations etc.) and each group developed a systems map of the air pollution challenge in the province.

The process led to the identification of the key air pollution sources to be represented in the model, their drivers and their impacts, and possible policy interventions. Sources of air pollution varied in terms of their importance across the provinces but included agricultural production (burning and chemicals), forest fires, waste burning, transportation, household cooking, and industrial activities and construction.

Following the workshop, the technical model development team in the Millennium Institute integrated the systems maps and developed Causal Loop Diagrams (CLDs) for key sources and drivers of air pollution in the province. These CLDs were then further refined through feedback from UNDP and were used to inform the subsequent model development process.

1.2.2 Model design and implementation and model review and validation

The model design process was undertaken through several steps, including data collection, literature review and formalization of the system variables and feedbacks as a stock-and-flow system dynamics model. The co-generated knowledge from the stakeholder workshops formed the basis for an initial shared understanding of the issue from a dynamic perspective, and was integrated with available data and literature for Thailand and Laos (and specifically the Chiang Rai and Vientiane provinces), however the model was also designed to be readily adaptable to other locations (at the subnational level). The model documentation sets out the fundamental dynamics that the model generates and well as the scope, theory and data used to develop the model.

In terms of scope, the model is developed at the sub-national (provincial) scale, incorporates annual simulations over the period to 2030, includes 18 pollution source activities, three main types of pollutants (PM2.5, NO_2 and SO_2) and 12 different policy interventions most of which are formulated as investment. Source activities in the model are estimated based on key drivers associated with demographics, economic growth, tourism, education and awareness. The model is calibrated based on data for drivers, source activities, air pollution concentrations, health impacts and other indicators.

The model includes a 'back-end' built in the system dynamics modelling language and comprises seven modules. The model estimates the emissions of air pollutants associated with different source activities (transport, forest fires, agriculture, waste, industry, households and cross-border emissions) and converts these to concentrations using dispersion modelling. Health impacts associated with exposure to annual mean air pollutant concentrations are then estimated, which then feedback to the key model drivers. Policy interventions are associated with the main sources and are designed to reduce or abate emissions from these sources or mitigate health impacts.

The model 'front-end' is in the form of a user-friendly scenario simulation interface developed for each province (Chiang Rai, Vientiane). The user interface provides a concise overview of the model development process and each of the modules, and is designed to help stakeholder better understand the key sources and drivers of air pollution, their implications for health and socio-economic development, and potential policies and interventions to address this challenge. The user interface can be used by governments and other stakeholders to run scenario analysis simulations to explore the effects of different assumptions and policy interventions on air pollution and associated impacts over the period to 2030. A video tutorial (Chiang Rai, Vientiane) and model user manual were developed for each province to support implementation.

Importantly, the user interface incorporates a main simulation page for reviewing the baseline projection and for running different policy scenarios. Each of the 12 policies includes information regarding how the policy was formulated and key assumptions. Each policy (except for regional cooperation) is formulated as a level of investment or expenditure which can be adjusted in the user interface in the form of different policy scenarios. The efficacy and costs associated with each intervention are estimated based on available published literature and data. The annual costs and magnitude of impacts for different interventions are difficult to estimate. Given the uncertainty, the user interface also allows for these assumptions to be adjusted by the user.

A model review and validation process was undertaken with UNDP and project stakeholders over the period from August 2022 to February 2023. The process was iterative with multiple rounds of feedback and revisions which primarily focused on ensuring a comprehensive and intuitive design for the model user interface. Once the model was finalized, the baseline or business-as-usual projection was simulated and presented in the model user interface. This included a 'more results' page which enables users to view timeseries charts for different air pollutant concentrations and source activities as well as other indicators.

1.2.3 Scenario Analysis and Training

The final activities included scenario analysis and training workshops held in Chiang Rai and Vientiane provinces in February and March 2023. The objectives were to provide training to stakeholders in using the model user interface and undertake participatory policy investment scenario analysis and identify and discuss policy priorities for the air pollution challenge in each province. This included introductory presentations by stakeholders, viewing of the model video tutorials, walk-through by the model development team, as well as scenario simulation activities. Participants reviewed and discussed the baseline projections for their province, observing important sources of emissions based on the available data. Participants then undertook group-based scenario 'gaming' exercises where they were allocated a set budget (THB 5 billion or USD150m) to address the air pollution challenge by 2030 and tasked with identifying a set of priority interventions that delivered the strongest reductions in air pollution. Through the workshop, participants developed their own policy scenarios and key findings, gaps and recommendations were recorded and discussed.

1.3 Summary of Final Project Deliverables

In addition to this final project report, the following final deliverables were submitted at the completion of the project and in accordance with the project work plan:

1. Final system dynamics models for Chiang Rai and Vientiane provinces: this includes the stock-and-flow models built in Stella Architect along with their input files and datasets as well as the online model user interfaces available through the ISEE exchange.
2. Model documentation and primary dataset and sources for Chiang Rai and Vientiane provinces
3. User manual and video tutorials for Chiang Rai and Vientiane provinces
4. Scenario analysis workshop reports for Chiang Rai and Vientiane provinces

The commercial Stella Architect software was used to develop both the model back-end and front-end. While the model front-end or user interface is freely accessible online and can be used to run model simulation, a software license is needed to interact with and make revisions to the model back-end. In addition, technical training in quantitative system dynamics modelling is also necessary to develop capacities needed to interact with the model back-end and formal stock-and-flow structure of the model. This presents some limitations in terms of further developing the model structure to incorporate new policy interventions and different sources of pollutants, or for recalibrating the model if new data becomes available.

2. Key Findings and Recommendations – Chiang Rai and Vientiane Provinces

The development and implementation of the IAP model for each province including the policy scenario simulation exercises resulted in a range of important findings and recommendations relating to the transboundary air pollution challenge in the region. These are briefly summarized here for each province.

2.1 Chiang Rai Province

The model baseline projection for Chiang Rai for 2030 projected a mean annual concentration for PM2.5 of 27.95 mg/m^3 (urban) and 16.84 mg/m^3 (rural). The major contributors to annual PM2.5 emissions from within the province in 2030 are projected to be waste burning (875,100 kg/year PM2.5), transport (829,200 kg/year PM2.5), and household cooking (365,300 kg/year). Other significant contributors include agricultural processing (139,700 kg/year) and forest fires (47,800 kg/year), while agricultural burning and industrial emissions were smaller contributors. As such, the projection results indicate that the majority of annual PM2.5 emissions from within the province can be attributed to waste (38.6%), transport (36.6%) and households (16.1%) – together amounting to 91.3% of emissions from within the province. However, another major contributor to PM2.5 concentrations is cross border emissions which were estimated at approximately 10.32 mg/m^3 per annum in 2030. Without these contributions, concentrations in the region would decline by close to 37% in urban areas and 60% in rural areas.

During the discussions with stakeholders, emphasis was given to source activities such as forest fires and agricultural burning, due in part to the considerable disruption and visibility associated with these activities in the province. The small contribution of these sectors in the data suggests that these are not major contributors to average annual PM2.5 emissions. However, It is important to note some caveats associated with these results.

Firstly, the model projects *annual* concentrations of air pollutants and as such the emissions contributions are aggregated values over the course of a whole year. Activities such as transport are generally significant throughout the year and as such are major contributors to annual emissions. Other source activities such as forest fires or agricultural burning are more seasonal and while they may be large contributors in a particular month where there is high activity, the total contribution over the course of a year may be comparatively less. Annual concentration values are important for simulating health effects from chronic exposure, which is a key objective for the model. However, the discussions suggest that seasonal or intra-annual variability in emissions is another important consideration in terms of targeting policy investments, as it can result in short-term disruptions and health effects which are not currently simulated.

Secondly, the model is calibrated based on available provincial data on source activities. As such, the accuracy of the simulations is influenced by the quality of available data. In the case of forest fires and agricultural burning, annual data on biomass burned in forest fires and agricultural residues was sourced from the Thai Government (Forest Fires Control Division) and FAO. However, it is difficult to assess the comprehensiveness and accuracy of these datasets which introduces uncertainty into the model projections. If these datasets underestimate these source activities in the province, then this would flow through as underestimates int the model projections. Potential solutions include further effort in verifying and collecting new data on these sources. This could be seen as a priority given the importance of these sources to participants.

Thirdly, the large contribution of cross-border emissions to provincial concentrations is not broken down by source activity and it is likely that these emissions include a mix of activities including forest fires and agricultural burning, amongst others. As such, control of forest fires and agricultural burning in surrounding provinces would likely lead to reductions in concentration in Chiang Rai.

In terms of policy interventions, the prominence given to forest fires and agricultural burning as sources of pollution led stakeholders to invest more heavily in measures associated with these sectors. However, due to their limited overall contribution to average annual emissions, these interventions did not result in significant reductions in pollution concentrations in the province. Through the scenario simulation exercises, it was revealed that a combination of investments targeting all sources of emissions produced the greatest gains. Overall, a cumulative investment of THB5 billion over the period to 2030 delivered large reductions in PM2.5 concentrations in both urban (-38.3%) and rural (-23.7%) areas.

The largest real reductions in emissions per annum were achieved in the waste (-832.3 kg/yr), households (-328.6 kg/yr), and transport (-219.7 kg/yr) sectors with smaller gains in forest fires and agricultural burning and marginal improvement in agricultural processing. In terms of the cost effectiveness of the different policy investments, the simulation results suggest that investments to address emissions from household cooking and waste burning would be the most cost effective in terms of the emissions reductions per kg of emissions abatement per annum. These measures include investment in composting, recycling, waste management and clean cookstoves. These results highlight these sectors as potential 'low hanging fruit' for initial investment to reduce particulate emissions in the province.

Policy measures targeting the transport sector included electric vehicle, engine efficiency and engine filters also delivered substantial net reductions in transport emissions compared to the baseline projection. However, the continued growth in this sector was projected to override these emission reduction improvements. This is because the sector is particularly sensitive to future assumptions regarding population and income growth. Downstream or tale-pipe policy investments see a solid reduction in emissions when compared against the baseline projection, however these gains are overwhelmed by future growth in the vehicle fleet. Measures such as investment in electric vehicles will take many years to replace the existing internal combustion engine vehicle fleet and there is therefore considerable inertia in emissions from this sector.

For the forest fire and agricultural sources, the policy interventions included community forest fire management, sustainable agricultural training, and farming machinery. These measures reduced emissions for forest fires and agricultural burning, but had little effect on agricultural processing emissions. In the case of forest fires, the literature indicates that it is not feasible to 'eradicate' forest fires as a source of emissions as there is a natural baseline level. As such assumptions in the model limit the maximum achievable reduction in forest fire emissions. The future implications of climate change for this sector are also uncertain and could exacerbate this challenge, however these effects are not incorporated into the model. In the case of agricultural processing, the results indicate that the current suite of policies is not effective for this sector and would need to be expanded to address processing emissions.

Following the investment scenarios, the sectors with the largest remaining contributions to emissions suggest important areas of policy resistance, in particular in the transport sector (71% of remaining emissions) and agricultural processing (16.3% of remaining emissions). This highlights areas where additional policy action beyond the measures included in the model will likely be needed to make further improvements in controlling air pollutants. This could include additional upstream measures in the transport sector such as public transport and mode shifting as well as more targetd measures for the agricultural processing sector.

Regional cooperation also proved to be essential to reduce cross-border emissions and air pollution concentrations in Chiang Rai. Domestic cooperation with provinces to the south and west of Chiang Rai saw a reduction in cross-border emissions of around one-third (-31%) and a further drop in PM2.5 concentrations within Chiang Rai to 14.1 mg/m3 (including the policy investment scenario). International cooperation saw a further reduction of cross-border emissions of around 10%, and a final PM2.5 concentration of 13.1 mg/m3. The more significant reduction from domestic cooperation was due to assumptions regarding the prevalent wind direction and baseline levels from surrounding provinces. It was also noted that combining the policy investment scenario with both domestic and international cooperation resulted in strong overall reductions in PM2.5 concentrations within the province of over 50%, bringing the levels close to the WHO threshold (<10).

In summary, key findings and policy recommendations for Chiang Rai province include:

- Based on the model baseline projection, the main contributors to annual PM2.5 air pollution concentrations in the province in 2030 were waste burning, transport, household cooking, agricultural processing and forest fires.
- A package of complementary policy investments targeting all sources of emissions within the province combined with regional cooperation produced the greatest overall reduction in air pollutant concentration.
- Cost-effective policies that represent low-hanging fruit include those that target emissions from waste burning and household cooking, notably composting, recycling, waste management and clean cookstoves.

- Investment in transport policies are also important to reduce emissions from this sector, however they are more expensive and the projected improvements are drowned out by rapid growth in the sector. This suggests the need for additional upstream policy measures such as public transport and mode shifting.
- While the data and simulation projections suggest that sources such as forest fires and agricultural burning are modest contributors to annual emissions, they are important point source contributors in particular months of the year. Additional exploration of the short-term variability and impacts of these sources and potential options to address them remains an important priority for stakeholders in the region. Priority should be given initially to improving data relating to these sources which would allow a 'deeper dive' into temporal and spatial variation along with a broader suite of targeted policy measures for these sectors.
- A final policy recommendation relates to the further identification and development of additional measures to reduce emissions specifically from agricultural processing. This could be considered a longer-term priority as it increases in importance over the period to 2030 as other sources are reduced.

2.2 Vientiane Province

The baseline or Business-as-Usual (BAU) scenario for 2030 for Vientiane showed a projected concentration of PM2.5 of 29.26 mg/m3 (urban) and 18.42 mg/m3 (rural). The major contributors to annual PM2.5 emissions from within the province in 2030 are projected to be households (2.7m kg/year PM2.5), industry (2.6m kg/year PM2.5), transport (1.0m kg/year PM2.5), and waste burning (900,600 kg/year PM2.5). Other contributors included agricultural processing (25,500 kg/year) and forest fires (80,400 kg/year), while agricultural burning was projected to be minor contributor. As such, the projection results indicate that the majority of annual PM2.5 emissions from within the province can be attributed to households (36.6%), industry (35.6%), transport (14%) and waste burning (12.3%). However, another major contributor to PM2.5 concentrations is cross border emissions which are estimated at approximately 15.12 mg/m3 per annum in 2030.

During the discussions with stakeholders, waste burning and household cooking were seen as prominent sources of air pollution in the province, while cross-border and industrial sources were not well-recognized as key sources of emissions. This may be due to the greater visibility of pollution associated with waste burning and cooking. While the number of industrial facilities in the province may be modest, single industrial facilities can be a considerable source of emissions and cross-border emissions. Industrial activities also included cement and construction activities which are not necessarily associated with heavy industry. However, the paucity of quality data in the province also presents a challenge and introduces uncertainty into these projections. Improving data on key source activities in the province would facilitate verification of the model estimates and improved projections.

During the scenario simulations, stakeholders discussed a number of considerations that could guide where to make investments. Firstly, targeting investments at the largest contributing sectors of emissions identified by the baseline projection were observed to result in the strongest gains in terms of annual concentration levels. Based on the data, household cooking, industry and transport were recognized as the largest sources and waste also featured in the data and was also seen by participants as a dominant contributor.

Secondly, targeting the more cost effective and upstream policy measures could drive more rapid change, such as recycling and composting and the substitution of solid fuels with gas in household cooking. Stakeholders observed the more limited efficacy of downstream abatement measures in the transport and industry sectors. As noted also in Chiang Rai, the growth dynamics in these sectors tend to quickly override abatement measures, as growth in population, economies and income drive accelerated growth in the vehicle fleet and industrial development. This underscores the challenge in reducing emissions in sectors where rapid continued growth in baseline emissions is expected, as well as where abatement measures are comparatively much more expensive. The transport and industry sectors are particularly sensitive to future assumptions regarding population and economic growth.

The final results for the scenario simulations yielded a range of insights regarding opportunities to address the air pollution challenge in the province. Overall, the cumulative investment scenario involving a package of policies (up to 150m USD over the period to 2030) delivered moderate reductions in PM2.5 concentrations in both urban (-23.2 to -23.4%) and rural (-9.0 to -9.3%) areas. In terms of policy interventions, the prominence given to waste burning and households led stakeholders to initially invest more heavily in measures associated with these sectors. Through the scenario simulation exercises, it was revealed that strong gains were achievable from these sectors, and that combination of investments targeting all sources of emissions produced the greatest overall reduction in PM2.5 concentrations.

The largest real reductions in emissions per annum resulted from interventions in household cooking (-2.7M kg/yr), waste burning (-868.2k kg/yr) and transport (-414.8k kg/yr). In terms of the cost effectiveness of the different policy investments, the simulation results suggest that investments to address emissions from household cooking and waste burning would be the most cost effective in terms of the emissions reductions per kg of emissions abatement per annum. These measures include investment in composting, recycling, waste management and clean cookstoves. This again highlights these sectors as potential 'low hanging fruit' for initial investment to reduce particulate emissions in the province.

In the case of transport, the downstream or tale-pipe policy investments saw a solid reduction in emissions when compared against the baseline projection, however these gains were overwhelmed by future growth in the vehicle fleet. Measures such as investment in electric vehicles will take many years to replace the existing internal combustion engine vehicle fleet and there is therefore considerable inertia in emissions from this sector. Alternative policy settings around vehicle performance standards combined with improved public transport and mode shifting were seen as potential options in the transport sector.

Similarly, the abatement measures in the industry sector support some reduction in emissions however they are expensive and marginal in terms of the total emissions from the sector. Sustainable consumption and production approaches (e.g. enhanced circularity, fuel and material efficiency, renewable energy investment and carbon abatement technologies) could provide upstream options for reducing emissions in the industry sector.

Following the investment scenarios, the sectors with the largest remaining contributions to emissions suggest important areas of policy resistance, in particular in the industry (76.5 to 77.9% of remaining emissions) and transport (17.8 to 22.3% of remaining emissions) sectors. This highlights areas where additional policy action beyond the measures included in the model will likely be needed to make further improvements in controlling air pollutants. This could include additional upstream measures in the transport sector such as public transport and mode shifting as well as the industry sector such as greening industrial development.

The simulation results also suggest that international cooperation with surrounding provinces could deliver large additional reductions in air pollutant concentrations in Vientiane if these provinces adopted similar air pollution reduction measures. Domestic cooperation with the province to the north of

Vientiane saw limited additional gains due largely to the prevalent southerly wind direction, however baseline air pollution data for this province is lacking. International cooperation with provinces to the south delivered considerable additional reductions of around a half (~-55%) with a reduction in PM2.5 concentrations in Vientiane to 13.23 mg/m3 in urban areas (including the policy investment scenario). This would bring air pollution concentration in the province close to the WHO threshold (<10). However, it is noted that the limited available data on air pollution in surrounding provinces and on cross-border flows introduces uncertainty into these estimates. While addressing the national and subnational air pollution challenge within Laos was seen as the priority for stakeholders, the importance of regional cooperation through ASEAN was also recognized as critical to address air pollution.

A key challenge in the development of the model for Vientiane was the limited availability of provincial-scale data. As the model is calibrated on existing datasets for the province, the quality of this data has implications for the model projections. While data was available relating to important drivers in the model, data on key source activities was more limited and was drawn from a range of sources including provincial and national datasets, expert literature, global databases, and estimates based on national or regional data. The limited availability of quality provincial data introduces greater uncertainty into the model projections. Improving data collection and availability for the region, particularly regarding the main source activities would likely yield more robust projections. In particular, data on transport activity volumes, waste burning per capita, cooking activity volumes, and industrial production at the provincial scale were difficult to source. These would represent priorities for future data collection efforts to reduce uncertainty in the model projections. In addition, air pollution monitoring in surrounding provinces and data on cross-border emissions could also be prioritized to improve estimates of the contribution from these sources.

In summary, key findings and policy recommendations for Chiang Rai province include:

- Based on the model baseline projection, the main contributors to annual PM2.5 air pollution concentrations in the province in 2030 were household cooking, industry, transport, waste burning, forest fires and agricultural processing.
- A package of complementary policy investments targeting all sources of emissions within the province combined with regional cooperation produced the greatest overall reduction in air pollutant concentration.
- Cost-effective policies that represent low-hanging fruit include those that target emissions from household cooking and waste burning, notably clean cookstoves and composting, recycling, and improved waste management.
- Investment in transport policies is also important to reduce emissions from this sector, however they are more expensive and the projected improvements are drowned out by rapid growth in the sector. This suggests the need for additional upstream policy measures such as public transport and mode shifting.
- Investment in industry abatement measures resulted in modest reductions in emissions, however were more expensive and less cost-effective. Again, potential upstream measures could include sustainable consumption and production approaches (e.g. enhanced circularity, fuel and material efficiency, renewable energy investment and carbon abatement technologies).
- Estimates for cross-border emissions reveal the important contribution from surrounding international provinces. Enhancing international cooperation with these provinces (e.g. through ASEAN and other mechanisms) Will also be critical to address the air pollution challenge in the province.
- Provincial-scale data remains a critical challenge and introduces uncertainty into the model projections as the model is calibrated based on the best available datasets. Priorities for data collection efforts to improve the model projections would include data on transport activity volumes, waste burning per capita, cooking activity volumes, and industrial production at the provincial scale. In addition, air pollution monitoring in surrounding provinces and data on

cross-border emissions could also be prioritized to improve estimates of the contribution from these sources.

- Finally, and as noted, a broader suite of policy measures may need to be considered in sectors that are more stubborn to emission reduction efforts, particularly upstream measures in transport and industry. Further consideration of mechanisms for improving international cooperation are also worth exploring in more depth. These could be considered longer-term investment priorities for addressing the air pollution challenge in the province, and will become more crucial over time with continued projected growth in population and income.

3. Project Outcomes, Lessons Learned and Next Steps

3.1 Future use and deployment of the model

The model user interface for each province provides a tool for stakeholders and decision makers to explore the air pollution challenge, to increase understanding of key sources and potential interventions based on the best available data, to prioritize future investments in terms of their cost-effectiveness in reducing annual pollution concentrations with a focus on PM2.5 emissions.

The scenario simulations undertaken in each province demonstrate that implementing a provincial-scale policy investment framework to address air pollution could see strong improvements in annual concentrations of PM2.5 as well as chronic exposure and health impacts. The model could thus be used as a tool to support initial policy prioritization by governments at different scales and estimate investment requirements associated with particular emission reduction outcomes. This could provide evidence to support government expenditure as well as programming by governments, partners and stakeholders.

To serve this purpose, it is recommended that the IAP model interfaces and associated materials be hosted in an accessible location on a government or partner organization website and that additional awareness raising, distribution of the video tutorials, and training activities be carried out in the use of the model interface. Complementing this, it will be important to raise awareness of the model purpose, capabilities and limitations which would be assisted by building knowledge and understanding of systems methods and models as well as data sources, gaps and uncertainty.

This would be supported through the development of technical capabilities in the region. Future development, enhancement and calibration of the model would require specialist software and training in system dynamics modelling. This capability could be developed at the domestic level but would require investment in the Stella Architect software (USD3,700 per license) as well as in training courses for staff. There are many training materials and webinars freely available and accessible online, as well as more comprehensive options available for building modelling capabilities. For example, the Millennium Institute runs an annual intensive course on system dynamics for policy analysis through the University of Bergen. An evaluation version of the Stella Architect model is also available (30 day limit) as are cheaper licenses for students and teaching purposes. The benefit of building domestic modelling capability would be that countries could better interrogate and verify the underlying assumptions in the model, and further develop and enhance the model as needed.

3.2 Developing Policy Investment Frameworks: Prioritization of policies using the model interface

The project yielded a range of insights with regard to the prioritization of policies to reduce annual concentrations of air pollutants which were broadly consistent across both provincial applications. The stakeholder engagements and scenario simulations underscored the importance of guiding investment decisions using available evidence and data on sources of air pollutant emissions and the efficacy of interventions in mitigating these sources. Given the perceived importance of some sectors as key sources of air pollution, there was a tendency to invest larger sums in these sectors. However, balancing investment through a portfolio of measures targeting all sources generally yielded the greatest reductions in concentrations overall.

In both provinces, responsive sectors such as household cooking and waste burning were seen as "low hanging fruit" to be fast tracked to reduce ambient concentrations. These would represent initial priorities for governments and stakeholders in both provinces to begin discussing potential investment opportunities with partners to finance interventions such as composting and recycling and the rollout of clean cookstoves.

Longer-term policy attention could then be given to more resistant and expensive sectors over time, such as transport and industry. For transport, this would include incentives for electric vehicles and more efficient vehicles as well as improved engine filters. In the case of industry, improved monitoring and regulation of emissions from this sector could drive the necessary investment in abatement technologies and measures. However, such measures are comparatively expensive and may also require support or incentives from government. To better address the air pollution challenge from these sectors, a deeper dive into additional upstream policies would be warranted and would be a potential priority for future research and model development.

A particularly problematic area for policy development related to emissions from forest fires and agricultural burning, which featured in the stakeholder discussions from Chiang Rai. While the data and simulation projections suggest that sources such as forest fires and agricultural burning are modest contributors to annual emissions, they are important point source contributors in particular months of the year. Additional exploration of the short-term variability and impacts of these sources and potential options to address them remains an important priority for stakeholders in the region.

3.3 Lessons learned on key model limitations and areas for further development

The development of the pilot IAP models for Chiang Rai and Vientiane provinces yielded a range of broader insights and lessons learned. The models were developed to simulate all major sources of emissions associated with key air pollutants including PM2.5 emissions. This broad scope provides a holistic picture of important sources of air pollutants within the province along with a broad suite of policy measures that could be used to address the air pollution challenge. This broad scope was important to ensure transferability of the model to other provinces where important source activities may vary. However, the broader scope of the model meant that the depth of projections and interventions in specific sectors was more limited. An example of this drawback was seen in the model for Chiang Rai province where stakeholders desired greater focus and detail for the forest fires and agricultural burning source activities. Given the strong stakeholder interest in these sectors, any future model development for this province should seek to provide greater detail on the air pollution challenge and potential solutions specifically for these sources. However, to do so would require further temporal and spatial disaggregation of the model which would be hampered by data gaps.

Related to this, and due in part to data constraints as well as the intended focus on chronic and long-term health impacts, the model projections focused on average annual emissions and concentrations of PM2.5. The largest contributors to annual emissions were generally associated with source activities with continuous levels of emissions throughout the year. Other more visible sources, such as those associated with smoke from forest fires and burning were more intermittent and the available data suggested that these were only modest contributors to annual pollution levels. However, it is important to recognize that these source activities would likely be very disruptive in certain months of the year and may have a range of impacts beyond chronic exposure to air pollutants.

The broad scope and annual temporal scale of the current pilot models therefore have some important limitations which need to be acknowledged which meant that some sources and issues of importance to the stakeholders could not be evaluated in-depth by the model. As the model is calibrated on existing datasets for the provinces, the quality of data also has implications for the reliability of model projections. Improving data collection and availability for the region, particularly regarding the main source activities would likely yield more robust projections. To support the improvement of future model projections, priorities for data collection and verification were identified for each province, as were priority areas for future model development.