HHS Public Access
Author manuscript
Disaster Med Public Health Prep. Author manuscript; available in PMC 2016 December 01.

Published in final edited form as:
Disaster Med Public Health Prep. 2015 December ; 9(6): 634–641. doi:10.1017/dmp.2015.105.

Assessing the capacity of the healthcare system to use additional mechanical ventilators during a large-scale public health emergency (PHE)

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Abstract

A large-scale Public Health Emergency (PHE), like a severe influenza pandemic can generate large numbers of critically ill patients in a short time. We modeled the number of mechanical ventilators that could be used in addition to the number of hospital-based ventilators currently in use. We identified key components of the healthcare system needed to deliver ventilation therapy, quantified the maximum number of additional ventilators that each key component could support at various capacity levels (i.e. conventional, contingency and crisis) and determined the constraining key component at each capacity level. Our study results showed that U.S. hospitals could absorb between 26,200 and 56,300 additional ventilators at the peak of a national influenza pandemic outbreak with robust pre-pandemic planning. This methodology could be adapted by emergency planners to determine stockpiling goals for critical resources or identify alternatives to manage overwhelming critical care need.

Keywords

mechanical ventilators; critical care; surge; capacity; public health emergency; crisis; influenza; model; supplies; staff; space; systems; respiratory; capability; stockpile; planning; hospitals; coalitions; resources; preparedness

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Potential conflicts of interest

All authors report no conflicts of interest relevant to this article.

Introduction

Large-scale public health emergencies (PHEs) due to an influenza pandemic, chemical, biological, radiological, and nuclear (CBRN) agents can generate large numbers of patients with respiratory illness in a short time. Therefore, the U.S. health care system must be prepared to meet a large surge in the number of patients that would need respiratory care. Illustrating the potential for increased need for mechanical ventilation, a study of 47 Maryland hospitals over a period of 12 years, including the 2009 H1N1 influenza pandemic, found a statistically significant 7% increase in mechanical ventilator use during intense influenza periods compared to non-influenza periods. (1) Erikson et. al. also found that 7% to 9% of pediatric patients admitted to 43 U.S. children's hospitals with seasonal influenza and presumed 2009 pandemic H1N1 influenza needed mechanical ventilation. (2) To manage potentially larger surges in respiratory illness that could be caused by a virulent influenza strain, the U.S. Federal government maintains in the Strategic National Stockpile (SNS) a supply of mechanical ventilators that can be distributed to U.S. hospitals in a large-scale PHE.

Many acute care hospitals maintain an inventory of mechanical ventilators on site to match routine patient care needs; additional units can be procured or leased from medical supply vendors as needed. (3, 4) One study estimated that U.S. acute care hospitals own approximately 62,000 full-feature mechanical ventilators, of which 24,000 (39%) has the capability to ventilate pediatric and neonatal patients. The study also reported an additional 98,000 ventilators that are not full-featured but are maintained in U.S. hospitals. (5) However, it is uncertain what proportion of these ventilators are in use at any one time or what capacity is available in the U.S. healthcare system to absorb a surge in mechanical ventilation need.

The current U.S. health care system may have limited capacity to use additional mechanical ventilators during a large-scale PHE. In this paper, we provide a model to estimate the surge capacity of the U.S. health care system to use additional or stockpiled mechanical ventilators. This assessment includes identifying health system components (supplies, space, staff and systems) that may constrain the number of ventilators that could be effectively used during the peak of a national influenza pandemic outbreak. The methodology used for this assessment can be adapted by emergency planners at the facility, local, and state level to: 1) project critical care surge capacity; 2) determine stockpiling goals for critical care resources; 3) identify gaps in emergency preparedness; or 4) identify alternatives to manage overwhelming critical care need.

Methods

Ventilator Capacity-based Assessment

We assessed the capacity of the U.S. healthcare system to rapidly absorb additional mechanical ventilators during a large-scale PHE using the following steps. First, we identified the key components of the healthcare system needed to effectively deliver ventilation therapy to patients. Secondly, we quantified the maximum number of additional ventilators that each of the key components could effectively support at various capacity levels (i.e., conventional, contingency and crisis). (6) According to the Institute of Medicine (IOM), conventional capacity is defined as the usual and normal patient-care where facilities and staff meet their normal goals in providing care. Contingency capacity requires minor adaptation that may have minor consequences for standards of care, but adaptations are not enough to result in significant changes to standards of care. Crisis capacity is defined as a fundamental, systematic change in which standards of care are significantly altered in order to allow treatment of a greater number of patients. (6) Third, we determined the constraining key component at each capacity level to determine the system's surge capacity.

Components necessary to provide mechanical ventilation

The four key components necessary to provide ventilation therapy to a patient include the necessary equipment such as ventilators and ancillary supplies including circuits and bacterial filters (supplies), hospital beds equipped for ventilation and comprehensive critical care (space), and specialized medical personnel to manage patients on mechanical ventilators (staff). (3) There is also a need for readily accessible and exercised plans to rapidly increase capacity for patients that require mechanical ventilation (systems) (Figure 1).

Quantification of healthcare components

The estimated number of ventilators that can be used is the key outcome component for this study. Staffed beds are the key input component for space. Specially trained critical care physicians, nurses and respiratory therapists are the key input components for staff. The systems input component, for example planning and communications, is difficult to quantify. Thus, it was not considered in this assessment. As a result, quantification of healthcare input components was limited to the space and staff as outlined below.

Space—Bed space for patients that need mechanical ventilation requires specific functionalities such as electricity, oxygen, suction, medical gas, and monitoring equipment. In acute care hospitals, these functionalities are usually found in critical care or intensive care units. In a large-scale PHE, additional critical care space could be created through the use of intermediate care beds (e.g. step-down beds, post-operative care beds, and emergency care beds) and potentially general ward beds that could be equipped with the functionalities needed to provide ventilation care. (3)

To understand the space (i.e., excess beds) available to provide ventilation care at the different capacity levels, we obtained the estimate of staffed beds in the U.S. by bed type (7) and calculated the proportion of staffed beds that would be available to treat a surge of patients needing mechanical ventilation. Staffed beds are beds for which trained staffs are on hand and physically available to care for patients. (8) Recent data indicate an annual average availability of 32% for both critical care and non-critical care beds. (9 – 11) However, the literature suggests that annual averages in bed availability do not reflect weekly and seasonal variation. (12) As a result, we assumed a lower 10% to 20% bed availability across all capacity levels to address ventilation need at the peak of an influenza pandemic outbreak (8 – 10 days). Our 10% to 20% bed availability assumption was also informed by expert opinion.

At the conventional capacity level, we assumed only currently staffed but unoccupied critical care beds would be available for use by ventilated patients. At the contingency capacity level, we included staffed but unoccupied intermediate care beds (e.g., step-down beds, postoperative care, and emergency department beds) in our estimate of bed surge capacity. (7) At the crisis capacity level, we expanded bed space to staffed but unoccupied general ward beds that could be equipped with capabilities to support ventilated patients. (7) We excluded specialty care beds such as neonatal intensive care unit (NICU) beds, nursery beds, psychiatric beds, rehabilitation beds and nursing home beds. These beds were judged by subject matter experts as either unsuitable for general patient needs because they were specific to a patient population (i.e. neonates, newborns, or older adults), or have limited surge capacity. (7) We calculated the number of beds available for use by ventilated patients at the peak of an influenza pandemic for each capacity level by multiplying the number of staffed beds in each bed type category (e.g., intermediate, general ward) in the U.S. healthcare system by the previously described 10% – 20% peak bed availability.

Staff—Management of patients on mechanical ventilators requires a team of critical care personnel to optimize clinical outcomes. Personnel trained in the management of patients on mechanical ventilators include critical care physicians, critical care nurses, and respiratory therapists. In a large-scale PHE where critical care personnel are likely to be in short supply, staff capacity could be enhanced at the contingency and crisis capacity levels by: 1) extending provider working hours; 2) increasing patient to provider ratios (i.e. more patients per provider); and 3) augmenting critical care personnel with non-critical care personnel using a two-tier staffing model. In a two-tier staffing model, non-critical care personnel assume the more general aspects of patient care and function under the direct supervision of critical care personnel. (13 – 15) However, enhancement of staff capacity could be constrained by: 1) unacceptable extensions of work hours for trained personnel; 2) staff absenteeism due to personal illness or the need to care for others who are ill and; 3) inability to quickly and sufficiently train healthcare personnel who have no prior critical care experience to manage patients on mechanical ventilators.

To calculate the number of staff that would be available to treat a surge of patients on mechanical ventilators, we assumed that: 1) the number of trained medical personnel would correlate with the number of staffed beds maintained by hospitals; 2) medical personnel would work one 12-hour shift per day; and 3) 10% to 20% of medical personnel would be available as surge capacity, consistent with the 10% to 20% staffed bed availability assumption. While we did not take absenteeism of healthcare workers into account explicitly in the model, we did perform a sensitivity analysis to examine the impact of absenteeism on staff availability, as described below. Other staff assumptions were specific to the capacity level. At the conventional capacity level, health provider projections were limited to critical care personnel who primarily manage patients on mechanical ventilators (i.e., critical and pulmonary care physicians, critical care nurses, and respiratory therapists). (3) At the conventional capacity level, we assumed a patient to physician ratio of 10:1 to 15:1 (17), patient to critical care nurse ratio of 1:1 (15), and patient to respiratory therapist ratio of 4:1 to 6:1. (18)

At the contingency capacity level, the type of physicians delivering care to ventilated patients were expanded to include other medical specialties such as anesthesiologists, emergency care physicians, and cardio-thoracic surgeons with experience in managing patients on mechanical ventilators. In addition, the ratio of patient to healthcare provider was expanded for respiratory therapists and critical care nurses. At the contingency capacity level, we maintained a patient to physician ratio of 10:1 to 15:1 (17), expanded the patient to critical care nurse ratio to 2:1, (15) and expanded the patient to respiratory therapist ratio range to 7:1 to 9:1. (18)

At the crisis capacity level, critical care personnel were augmented with non-critical care personnel using already described two-tier staffing model. Each supervisory critical care physician would work with up to four non-critical care physicians. Each non-critical care physician would manage up to six patients, providing a patient to critical care physician ratio of 24:1 consistent with the Task Force for Mass Critical Care recommendations for physician two-tier staffing model. For critical care nurses, we assumed that three non-critical care nurses would work under the supervision of a critical care nurse, and each non-critical care nurse would manage up to two patients, providing a range of patient to critical care nurse ratio of 3:1 to 6:1. (15) Similarly, for respiratory therapists, we assumed that up to four respiratory extenders would work with a respiratory therapist and each respiratory extender would manage up to three patients, providing a range of patient to respiratory therapist ratio of 10:1 to 12:1. Respiratory extenders could be respiratory therapists working in administrative positions, respiratory therapy students, nurses and other healthcare professionals involved in patient care. (14, 15) All of the patient to staff ratios used for contingency and crisis capacity levels in this assessment were previously recommended by the Task Force for Mass Critical Care and Project extreme. (13 – 15) Finally, to project the number of medical personnel that would be available at each capacity level, we divided the number of staff in each medical personnel category by the number of shifts per day (two shifts per day), and multiplied the outcome by the 10% to 20% staff availability. This value was then multiplied by the patient to provider ratio to obtain the number of patients that could be treated for each medical personnel category at the peak of an influenza pandemic outbreak.

Sensitivity analysis—We tested the impact of varying the assumptions for space and staff availability on additional ventilation capacity. We varied the bed availability estimate from 10% to 20%, to 20% to 60% in a step-wise fashion across all capacity levels based on the range of bed availability data across U.S hospitals. (9 – 11) We also assumed a 20% reduction in staff availability due to staff absenteeism. (16) All other factors and assumptions remained the same.

Results

Space

As of November 2013, there were an estimated 1,098,849 staffed beds in the U.S. healthcare system. (7) Of these, 81,790 (7%) were adult and pediatric critical care beds, 180,000 (17%) were intermediate care beds (step-down beds, post-operative care beds, emergency care bed), 212,587 (19%) were specialty care beds (neonatal ICU beds, nursery beds, psychiatric beds, rehabilitation beds and nursing home beds), and 624,472 (57%) were general ward beds (Table 1). (7)

At the peak of an influenza pandemic outbreak, 8,200 to 16,400 additional patients could be ventilated nationally based on 81,790 critical care beds in the U.S. healthcare system and 10% to 20% bed availability at the conventional capacity level (Table 1). At the contingency capacity level, 26,200 to 52,400 additional patients could be ventilated nationally based on 261,790 intermediate care beds in the U.S. healthcare system and 10% to 20% bed availability (Table 1). At the crisis capacity level, 88,600 to 177,300 additional patients could be ventilated nationally based on 886,262 general ward beds (non-specialty care beds) in the U.S. healthcare system and 10% to 20% bed availability (Table 1). The contingency and crisis capacity level increased the number of staffed beds available to ventilate patients approximately three-fold and eleven-fold respectively over the conventional capacity level (Table 2).

Staff

As of November 2013, there were an estimated 799,500 physicians in the United States. (20) About 12,600 (1.6%) were critical care and pulmonary care physicians, 41,690 (5.2 %) were anesthesiologists, 35,650 (4.5%) were emergency care physicians, 4,730 (0.6%) were cardio-thoracic surgeons, and 704,830 (88.1%) were other physician specialty or primary care physicians. (19 – 22) The number of respiratory therapists was estimated to be 112,500 (23) while critical care nurses were estimated to be 503,124. (24) Based on this number of healthcare workers in the U.S. healthcare system, a 12 hour shift per day, 10% to 20% staff availability and patient to healthcare worker ratios described in the methods section, we projected the number of additional patients that could be treated nationally at the peak of an influenza pandemic outbreak for the different healthcare worker categories at the three capacity levels. At the conventional capacity level there are sufficient critical care physicians to ventilate 6,300 to 18,900 additional patients; there are sufficient respiratory therapists to ventilate 22,500 to 67,500 additional patients; and there are sufficient critical care nurses to ventilate 25,200 to 50,300 additional patients (Table 1). At the contingency capacity level there are sufficient physicians to ventilate 47,800 to 143,400 additional patients; there are sufficient respiratory therapists to ventilate, 39,400 to 101,300 additional patients; and there are sufficient critical care nurses to ventilate 50,300 to 101,600 additional patients (Table 1). At the crisis capacity level there are sufficient physicians to ventilate 114,700 to 229,500 additional patients; there are sufficient respiratory therapists to ventilate 56,300 to 135,000 additional patients; and there are sufficient critical care nurses to ventilate 75,500 to 301,900 additional patients (Table 1). The contingency capacity level increased the number of additional patients that could be ventilated by physicians, respiratory therapists, and critical care nurses at least seven-, one and a half-, and two- fold, respectively, over the conventional capacity level. The crisis capacity level increased the number of additional patients that could be ventilated by physicians, respiratory therapists, and critical care nurses at least twelve-, two-, and three- fold, respectively, over the conventional capacity level (Table 1).

Ventilation capacity model output

This assessment showed that the capacity of the U.S. healthcare system to provide ventilation therapy could be constrained by different key components at each capacity level (Table 2). The number of available critical care physicians was the most constraining key component at the conventional capacity level, limiting the maximum number of ventilated patients to 18,900. The number of available critical care and intermediate care beds was the constraining key component at the contingency capacity level, limiting the maximum number of ventilated patients to 52,400. At the crisis capacity level, the number of available respiratory therapists was the key constraining component, limiting the maximum number of ventilated patients to 135,000. (Table 2) This assessment showed that even if bed capacity and some staff capacity could be expanded by including general ward beds and employing the services of noncritical care physicians and nurses, U.S. ventilation capacity would still be limited by the number of trained respiratory therapists at the crisis capacity level.

Sensitivity Analysis

Expanding staffed bed availability from 10% to 20%; to 20% to 60% expanded the surge capacity to treat patients two to three folds (Tables 2 and 3). This sensitivity analysis showed that the number of mechanical ventilators that could be absorbed during a public health emergency was most sensitive to the staffed bed availability assumption for the following reasons: (1) the shift in the staffed bed availability range was large (from 10% to 20%, to 20% to 60%); and (2) increase to staffed bed availability also increased the number of staff available. Therefore, these results emphasize the importance of accurate staffed bed availability information when responding to a large-scale PHE. While factoring in absenteeism did reduce the number of staff available, the effect in our model was far outweighed by the large increase in staffed bed availability for the reasons mentioned above.

Discussion

Summary of main findings

In a large-scale PHE, hospitals, healthcare coalitions, local, state and federal healthcare resources may be constrained. The objective of this assessment was to provide a method for projecting the capacity of the U.S. health care system to effectively use stockpiled mechanical ventilators in preparation for a large-scale PHE such as an influenza pandemic. This assessment showed that the number of additional mechanical ventilators that could be effectively used during the peak of a severe influenza pandemic ranged from approximately 26,200 to 56,300. This range represents the projected number of additional mechanical ventilators that could be effectively used by the U.S healthcare system at the lower boundary of contingency and crisis capacity levels. As we approach the upper boundary of the range at 56,300 ventilators, subject matter experts interviewed as part of this project expressed concern that various components of the health care system would become stressed and there is uncertainty that health care services could be effectively delivered.

Main public health implications

This capabilities-based approach provides several benefits for emergency planning: 1) provides emergency planners at all levels (local, state, federal) with a practical method for projecting levels of medical resources that could be used by taking into account the health systems' capacity to absorb these resources during an emergency; 2) provides an evidence-based analytical model for emergency planners to identify gaps in preparedness; 3) identifies alternatives to manage overwhelming critical care need; and 4) likely supports a more efficient allocation of scarce resources for stockpiling. Furthermore, the impact of increasing staffed bed availability in the sensitivity analysis highlights the importance of regional coalition planning to make hospital beds available during large-scale PHEs. This analytical approach was used to inform the Strategic National Stockpile ventilator stockpiling goal, identify national ventilation preparedness gaps, and create an evidence-based foundation for development of plans to improve national mechanical ventilation capacity and therefore overall influenza pandemic preparedness.

Limitations

This planning assessment provides a good method for assessing capacity, but has potential limitations. Since large-scale PHEs are rare, there may be limited data to inform some of the assumptions that are needed for similar assessments. The assumptions and data used in the assessment presented here at the contingency and crisis capacity levels were based on the best available evidence but were largely untested. In addition, we made simplified model assumptions to approximate surge capacity projections. For example, we assumed a static range for bed availability (10% to 20%) that does not account for daily variation in bed availability. Finally, we did not incorporate the "systems" component such as resource sharing among facilities in the same network, and additional factors such as communications and logistics planning, into this assessment as these factors and their potential impacts were difficult to quantify.

Conclusion

For effective planning, emergency planners at all levels need to understand their healthcare systems' capacity to expand care for a surge of critically ill patients and the capability to absorb additional resources. This assessment provides a model for projecting a healthcare systems' surge capacity for large-scale PHEs. This model can be adoption and adapted to assist emergency planners at the facility, local and state levels to identify gaps in emergency preparedness, determine stockpiling goals for critical care resources, or identify alternative policies and protocols to manage increased need for critical care resources in a large-scale PHE.

Acknowledgments

We thank the Health and Human Services Public Health Emergency Medical Countermeasures Enterprise Ventilator working group with membership from the Office of the Assistant Secretary of Preparedness and Response, the Centers for Disease Control, the National Institutes of Health, and the Food and Drug Administration and many other partners for their contributions to this work. We also thank Dr. Joanna Prasher for her editorial comments.

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Biographies

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Article Summary

The U.S. healthcare system has limited capacity to absorb additional mechanical ventilators during a large-scale public health emergency; therefore it is necessary for emergency planners to project critical care surge capacity for effective planning.

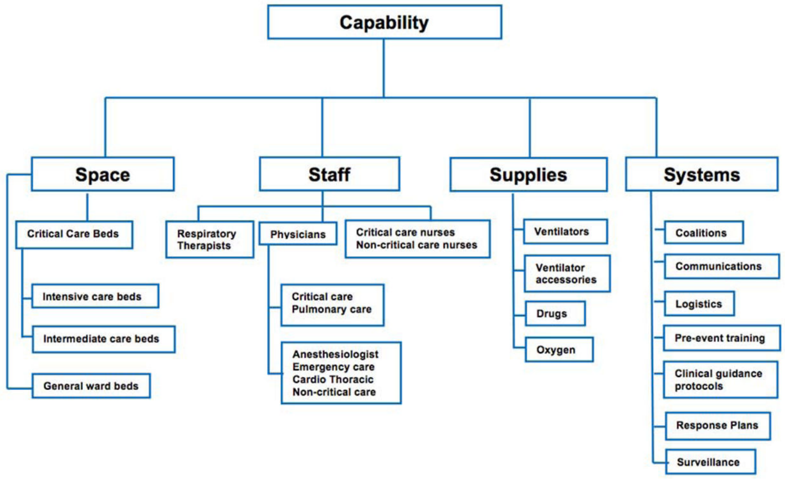

Figure 1.
Components needed for effective mechanical ventilation in response to a large-scale PHE

Table 1

Number of additional mechanically ventilated patients that can be treated at the peak of an influenza pandemic based on the available staffed beds and trained staff in the U.S. healthcare system by capacity levels.

Components		Conventional Level of Care					Contingency Level of Care					Crisis Level of Care				
Staff	**shifts/ day**	**Category**	**# in U.S**	**Patient/ staff ratio**	**% available**	**# of patients treatable**	**Category**	**# in U.S**	**Patient/ staff ratio**	**% available**	**# of patients treatable**	**Category**	**# in U.S**	**Patient/ staff ratio**	**% available**	**# of patients treatable**
Hospital bed		Intensive and critical care bed (adult & pediatric)	81,790		10%	8,179	Intensive, critical care bed (adult & pediatric) and intermediate care beds (step-down, post-operative, emergency care)	261,790		10%	26,179	Intensive, critical care bed (adult & pediatric), intermediate care beds (step-down, post-operative, emergency care) general ward bed	886,262		10%	88,626
					20%	16,358				20%	52,358				20%	177,252
Physicians	2	Critical care Pulmonary care	12,600	10:1	10%	6,300	Anesthesiologist Emergency care Cardio-thoracic surgeon	95,615	10:1	10%	48,000	Anesthesiologist Emergency care Cardio-thoracic surgeon	95,615	24:1	10%	115,000
				15:1	10%	9,450			15:1	10%	71,711				20%	229,500
				10:1	20%	12,600			10:1	20%	95,615					
				15:1	20%	18,900			15:1	20%	143,500					
Respiratory Therapy professional	2	Respiratory Therapists	112,500	4:1	10%	22,500	Respiratory Therapists	112,500	7:1	10%	39,000	Respiratory Therapists	112,500	8:1	10%	45,000
				6:1	10%	33,750			9:1	10%	50,625			12:1	10%	67,500
				4:1	20%	45,000			7:1	20%	78,750			8:1	20%	90,000
				6:1	20%	67,500			9:1	20%	101,300			12:1	20%	135,000
Nurses	2	Critical care	503,124	1:1	10%	25,000	Critical care	503,124	2:1	10%	50,000	Critical care	503,124	3:1	10%	75,500
				1:1	20%	50,000			2:1	20%	101,000			6:1	10%	151,000
														3:1	20%	151,000
														6:1	20%	302,000

Table 2

Constraining components by capacity level at the peak of an influenza pandemic

Components/subcomponents		Number of additional patients that can be ventilated national by capacity level		
		Conventional Capacity Level	Contingency Capacity Level	Crisis Capacity Level
Space	Beds	8,200 – 16,400	**26,200 – 52,400**	88,600 – 177,300
Staff	Physicians	**6,300 – 18,900**	47,800 – 143,400	114,700 – 229,500
	Respiratory Therapists	22,500 – 67,500	39,400 – 101, 300	**56,300 –135,000**
	Critical care Nurses	25,200 – 50,300	50,300 – 100,600	75,500 – 301,900

(ellipse) Indicate the constraining component at each capacity level.

Table 3

Sensitivity analysis of constraining components by capacity level at the peak of a an influenza pandemic

Components/subcomponents		Number of additional patients that can be ventilated national by capacity level		
		Conventional Capacity Level	**Contingency Capacity Level**	**Crisis Capacity Level**
Space	**Beds**	16,400 – 49,100	52,400 – 157,100	177,300 – 265,900
Staff	**Physicians**	10,100 – 45,400	76,500 – 344,200	183,600 – 550,700
	Respiratory Therapists	36,000 – 162,000	63,000 – 243,000	90,000 – 324,000
	Critical care Nurses	42,000 – 120,750	80,500 – 241,500	120,800 – 724,400

(oval) Indicate the constraining component at each capacity level.

Note: Inputs varied from table 2 in this sensitivity analysis.